

Technical Report 546

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# DETERMINATION OF MOTION AND VISUAL SYSTEM REQUIREMENTS FOR FLIGHT TRAINING SIMULATORS

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and

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ARI FIELD UNIT AT FORT RUCKER, ALABAMA

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Flight Training	Simulator Fidelity	Motion Perception												
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) <p>Fidelity requirements for Army flight training simulators are explored using a manual control theory approach. The first step is to define "simulator fidelity" in operational terms which provide a basis for each of the subsequent steps. This definition is accompanied by a taxonomy of measureable fidelity parameters. The next step, also of a preparatory nature, is the analysis of Army flight training missions. It describes how specific flight tasks and piloting techniques can be cast in terms</p>														

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compatible with feedback control theory. Pilot modeling techniques are then discussed, first in terms of pilot control and then in terms of pilot perception. Next, armed with compatible descriptions of fidelity, the training context, and pilot behavior, a procedure is described for studying visual and motion stimuli. It is found, however, that there are serious gaps in the experimental data base; and this precludes the systematic execution of this procedure. Because of the lack of data, it is not possible to accomplish fully the original objectives and, therefore, a formal bookkeeping scheme is outlined to guide the investigation of fidelity requirements. Conclusions and recommendations are then drawn. As aids to the reader, an executive summary and glossary of terms are provided.

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Robert K. Heffley, Warren F. Clement, Robert F. Ringland,  
Wayne F. Jewell, Henry R. Jex and Duane T. McRuer  
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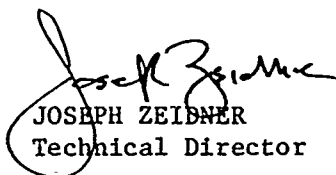
## FOREWORD

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The Army Research Institute Field Unit at Fort Rucker, Alabama, has the mission of providing timely research and development support in aircrew training for the US Army Aviation Center. Research and development are conducted in-house, augmented by contract research as required. This research report documents contract work performed as a part of the Field Unit's thrust in flight simulation development.

The development of validated requirements for flight simulator specifications is an area of intense interest for both DoD and industry. In this report, an approach is developed which will translate requirements based in human perceptual capabilities to requirements compatible with engineering specifications.

This work is responsive to Project 2Q263744A795, to the US Army Aviation Center, Fort Rucker, and to the US Army Project Manager for Training Devices (PM-TRADE).

  
JOSEPH ZEIDNER  
Technical Director

## DETERMINATION OF MOTION AND VISUAL SYSTEM REQUIREMENTS FOR FLIGHT TRAINING SIMULATORS

### BRIEF

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#### Requirement:

At present, there is no quantitative methodology for statement of flight simulator visual and motion systems requirements in terms of training objectives. This study uses available data relating visual and motion senses to pilot closed loop control and to spatial orientation and develops such a methodology.

#### Procedure:

First, fidelity is operationally defined in terms of the simulator's ability to induce the pilot trainee to output those behaviors and behavior patterns known to be essential to control and operation of the actual aircraft in performance of a specific task. From this definition, a control theoretic model of simulation training is developed consisting of a closed loop of three interconnected processes: the pilot's perception of task environment and simulator states, his control behavior technique, and the simulator's response. Then, the existing body of literature on simulation and simulation requirements is surveyed for data relevant to pilot perception and pilot technique.

#### Findings:

A control theoretic approach to training simulator requirements is shown to be a potentially powerful tool. But it is also shown that many areas of pilot control technique and dynamic perception are not sufficiently quantified.

#### Utilization:

The model developed here and the indicated areas in which additional, more quantitative research is needed will serve as a basis for an alternative approach to investigation of simulator visual and motion system requirements.

## ACKNOWLEDGEMENTS

The work reported herein was performed for the US Army Research Institute Field Unit at Fort Rucker, Alabama, under Contract MDA 903-80-C-0235. The Systems Technology, Inc., project engineer was Mr. Warren F. Clement and the Army Contracting officer's technical representative was Dr. William R. Bickley. Dr. Kenneth D. Cross of Anacapa Sciences, Inc., and Mr. Vernon E. Carter of Northrop were project consultants to Systems Technology, Inc. The final report manuscript was prepared by Mrs. Sharon A. Duerksen of Systems Technology, Inc. Work on the project was begun in February 1980 and completed in July 1981.

The authors gratefully acknowledge the contributions made by Dr. Kenneth D. Cross of Anacapa Sciences, Inc., and Dr. William R. Bickley of the US Army Research Institute Field Unit. Their efforts greatly aided in bridging the disciplines of control engineering and training psychology.

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## LIST OF ABBREVIATIONS

ADF	Automatic direction finder
AGARD	Advisory Group for Aerospace Research and Development
ARI	Army Research Institute
ATM	Aircrew Training Manual
CGA	Ground controlled approach
CGI	Computer generated image
CRT	Cathode ray tube
DG	Directional gyro
EPR	Engine pressure ratio
HD	Heave damping mode
IAS	Indicated airspeed
ICAO	International Civil Aviation Organization
K, kt	Knot(s)
IFR	Instrument flight rules
IMC	Instrument meteorological conditions
LAMARS	Large Amplitude Multimode Aerospace Research Simulator
LD	Lateral damping mode
LSF	Lateral specific force
NASA	National Aeronautics and Space Administration
NIPIP	Non-Intrusive Pilot Identification Program
NOE	Nap of the earth
OCM	Optimal control model
rad	Radians

RPM, rpm	Revolutions per minutes
SAS	Stability augmentation system
SCAS	Stability and control augmentation system
SD	Speed damping mode
sec	Seconds
SFTS	Synthetic flight training system
SOP	Successive organization of perception
S.P.R.R.	Southern Pacific Rail Road
STOL	Short takeoff and landing
TV	Television
UCLA	University of California at Los Angeles
VASI	Visual approach slope indicator
VFR	Visual flight rules
VMC	Visual meteorological conditions
VOR	Very high frequency omnirange
VTOL	Vertical takeoff and landing

# LIST OF SYMBOLS

$A$	(1) Subjective landing area size; (2) apparent distance of vanishing points from the principles of visual perspective
$A_{( )}$	Controlled element gain for ( ) state variable
$A_{y_p}$	Peak lateral specific force
$a_x$	Axial specific force
$a_y$	(1) Lateral specific force, (2) specific side force
$a_{y_{cab}}$	Lateral specific force
$C_L$	Centerline
$d$	Vertical flight path excursion
$e$	System error
$\dot{e}$	Error rate
$g$	Gravity constant
$g_y$	Spurious motion cues
$h$	Altitude
$\dot{h}$	Vertical velocity
$I_x$	Roll moment of inertia
$I_y$	Pitch moment of inertia
$I_z$	Yaw moment of inertia
$i$	System input
$j$	Imaginary operator
$K$ or $k$	Gain
$L_{( )}$	Roll stability or control derivative with respect to ( )
$L_r$	Roll stability derivative with respect to yaw rate
$L_\phi$	Roll stability derivative with respect to bank
$M_{( )}$	Pitch stability or control derivative with respect to ( )

$M_q$	Pitch stability derivative with respect to pitch rate
$m$	Aircraft mass
$p$	Roll rate
$q$	Pitch rate
$R$	Range
$\dot{R}$	Range rate
$\ddot{R}$	Deceleration
$r$	Yaw rate
$S$	Ground range, size
$s$	Laplace operator
$T_h$	Effective closed loop flight path lag
$T_I$	Pilot lag time constant
$T_L$	Pilot lead time constant
$T_R$	Roll mode time constant
$T_s$	Spiral mode time constant
$T_{sp_2}$	Helicopter pitch damping time constant
$T_u$	Effective closed loop airspeed lag
$T_{yd}$	Helicopter yaw damping time constant
$T_\theta$	Effective closed loop pitch attitude lag
$T_{\theta_1}$	Pitch numerator time constant
$T_{\theta_2}$	Pitch numerator time constant
$T_\delta$	Effective closed loop bank angle lag
$T_{\phi_1}$	Roll numerator time constant
$U$	Airspeed
$U_0$	Trim airspeed
$V$	Speed



$V_G$	Ground speed
$V_{MC}$	Minimum control speed
$V_{NE}$	Never exceed speed
$V_x$	Maximum angle of climb speed
$w$	(1) Runway width; (2) z-axis perturbation velocity component
$X$	X-axis force
$X_u$	Speed damping stability derivative
$X_{()}$	X-axis stability or control derivative with respect to ()
$x$	Distance along x-axis
$Y_c$	Controlled element transfer function
$Y_c(j\omega)$	Controlled element describing function
$Y_{cab}$	Simulator cab translational acceleration
$Y_p$	(1) pilot transfer function, (2) subjective lateral deviation
$Y_{pc}$	Pursuit command loop transfer function
$Y_{pe}$	Pursuit error loop transfer function
$Y_{pi}$	Pursuit input transfer function
$Y_{pin}$	Pursuit state measurement loop transfer function
$Y_p(j\omega)$	Pilot describing function
$Y_p Y_c(j\omega)$	Pilot-vehicle describing function
$Y_v$	Lateral damping stability derivative
$Y_{()}$	y-axis force stability or control derivative with respect to ()
$y$	Lateral displacement
$Z_{()}$	z-axis force stability or control derivative with respect to ()
$Z_w$	Heave damping stability derivative

$\alpha$	Angle of attack
$\beta_{\text{aero}}$	Aerodynamic sideslip angle
$\gamma$	(1) Actual depression from horizon, (2) nominal glide slope angle
$\Delta$	Incremental quantity
$\delta$	Control deflection
$\theta$	Pitch attitude
$\dot{\theta}$	Pitch rate
$\theta_c$	Pitch attitude command
$\lambda$	Backscattering coefficient
$\lambda_v$	Eyeball position
$\nu$	(1) Actual angle of centerline with respect to vertical, (2) approach line up centerline perspective angle, (3) nozzle deflection
$\pi$	3.14159..
$\sigma$	(1) Real part of Laplace operator, (2) Koschmeider's meteorological extinction coefficient
$\tau$	Time delay
$\tau_c$	Computing delays
$\tau_e$	Effective pure time delay
$\tau_{\text{eff}}$	Effective pilot time delay
$\phi$	Bank angle
$\psi$	Heading
$\omega_c$	Crossover frequency
$\omega_d$	Dutch roll frequency
$\omega_M$	Motion drive natural frequency
$\omega_{PL}$	Lateral phugoid frequency
$\omega_p$	Phugoid frequency

$\omega_{sp}$  Short period frequency

$\omega_y$  (1) High pass break frequency, (2) sway washout filter frequency

### SUBSCRIPTS

a Lateral control (aileron)

beam Simulator support beam

c (1) controlled element, (2) command, (3) collective control

cab Simulator cab

h Height

e (1) Error, (2) elevator control

I Lag

L Lead

m Measurement

o Objective

P (1) Pilot, (2) perceived

pk Peak

R Range

r Rudder control

U Airspeed

T Thrust control

t Threshold

v Visual

x Along aircraft fuselage reference line

y Perpendicular to fuselage reference line in lateral plane

$z$	Perpendicular to fuselage reference line in vertical plane
$\theta$	Pitch attitude
$\phi$	Bank
$\psi$	Heading, yaw

## **EXECUTIVE SUMMARY**

### **BACKGROUND**

Visual and motion simulator systems should be designed to address the specific training objectives which are of importance to the missions of Army aviators, but training objectives do not influence simulator designs as they should. There is presently little rationale for setting simulator specifications with regard to the specific training objectives of those simulators, and it is necessary to rely heavily upon past experience. If an existing simulator with given motion and visual system characteristics provides a successful transfer of training, then it is assumed that the same specifications should be used for the next simulator even though some of the specifications could be superfluous. Unfortunately there are no rules to tell us what to do if training was not successful. Was the deficiency in the motion or visual system? What must be done to correct that deficiency? What must be provided for new aircraft or new training objectives? These questions lead us to the objectives of this study.

### **OBJECTIVES AND SCOPE OF THIS STUDY**

The main objective of this study is to develop a methodology for approaching training simulator fidelity in terms which will ultimately permit rational system specification. A secondary objective has been to make use of available data where possible in order to exercise the methodology adopted and to set simulator fidelity requirements where it is possible. The scope of this study includes motion and visual fidelity considerations for a wide range of Army training objectives. These include fixed- and rotary-wing Army aircraft, operations in visual and instrument meteorological conditions, undergraduate through continuation

training, and recognition of critical flight phases which include nap-of-the-earth navigation, and weapon delivery.

## TECHNICAL APPROACH

The approach taken in this study is to formulate an operational definition of fidelity which decomposes the various aspects of fidelity which include training objective or task, piloting technique, pilot perception, and simulator model software and simulator hardware response. This decomposition yields a framework quantified in common terms which, in this case, are based on control theory ideas. The ultimate benefit of this approach is that the same terms used to describe the various components of the training scenario are, in fact, compatible with the terms used to write engineering specifications for simulator components. In effect there is a common frame of reference for system performance and fidelity measurement. Another important byproduct of this technical approach is that a number of natural constraints are automatically imposed as a result of quantification of the task and aircraft type. Further constraints are imposed by recognition of basic ideas from manual control theory. The ultimate reward is an analytic formulation of the task-pilot-aircraft system which describes the basic mechanisms of training to fly an aircraft as well as pilot performance with respect to desired flight tolerances.

## DEFINITION OF FIDELITY

This effort began with the development of an operational definition of simulator fidelity which sets the stage for all subsequent steps in achieving the study objectives. Briefly stated in verbal terms,

"Simulator fidelity is the degree to which characteristics of perceivable states induce correct psychomotor and cognitive control strategy for a given task and environment. This leads to special consideration of essential feedback loops required to execute a task and the essential cues provided by the simulator or training device which support those essential loops."

This definition of fidelity can also be depicted in a graphical form which clearly identifies the ideas of objective fidelity and perceptual fidelity. The implication is that it may not be necessary to have a highly veridical situation for skill development except in terms of the induced piloting technique.

#### **ARMY TRAINING MISSIONS**

A statement of fidelity is unavoidably conditional upon the training mission or task being addressed. It is necessary first to specify the various training missions to be considered for simulation, and this is done through direct reference to training literature and training syllabus material, supplemented by discussions with instructor pilots. This includes aircrew training manuals, aircraft flight manuals, descriptions of special missions such as helicopter gunnery or nap-of-the-earth flight. It also involves reviewing training material from other branches of the military as well as from civilian aviation. Guidelines are presented describing how to translate the training literature into a closed-loop system structure which is compatible with the engineering descriptions of the aircraft and the pilot psychomotor behavior. A number of task analyses are provided which illustrate the closed-loop nature of the task and provide some idea of the ranges of numerical quantification.

## PILOT MODELING TECHNIQUES

One of the central themes of the technical approach is to use manual control theory in pilot modeling techniques to aid in the analysis of simulator fidelity requirements. Some of the basic ideas in pilot modeling have been well developed; and it is possible to predict the nature of pilot behavior, especially psychomotor, given a good description of the task and of the vehicle. One of the more difficult aspects of pilot modeling is handling perceptual mechanisms, especially where visual information is involved.

## ANALYTIC PROCEDURE TO PREDICT CUE STIMULUS

With the ideas developed under the foregoing topics — definition of fidelity, description of Army training missions, and pilot modeling techniques — it is possible to devise a procedure which informs us of the cues required to perform training missions and whether those cues are, in fact, available in a given training device or simulator. This is a guide to discovering what cues are required and what cues may be lacking. Execution of this procedure requires a rather full numerical quantification of the task, piloting technique, vehicle and simulator response, and pilot perception. At this stage we find that the fragmentary nature of the available quantification of these characteristics prevents us from an effective analysis of visual and motion system requirements in general. Nevertheless it begins to point out what is needed in terms of additional research.



## **SIMULATOR FIDELITY BOOKKEEPING**

This step is a formalization of a procedure to take stock of simulator fidelity requirements. We specify a series of matrices which are comprised of basic data describing piloting technique versus task, cues available for various training devices, aerodynamic influences of the aircraft involved, and a series of matrices of constructed information which lead us to an ultimate statement of the training capability of particular devices and the motion and visual cue detail which must be specified when constructing a new device.

## **RESEARCH NEEDED**

This study demonstrates how simulator fidelity requirements can be specified in a rational way to address the wide range of Army training missions. At the same time, however, we find repeatedly that there are serious gaps in the basic experimental information required to exercise the rational analytic procedure. These gaps lie primarily in the pilot-centered areas involving piloting technique for specific tasks and pilot perception of motion and visual cues. In effect the data required are those which would fill out the basic simulator fidelity bookkeeping matrices previously described. The kinds of measurements to acquire these data are, by and large, feasible and can be comprised of several different approaches which can be applied simultaneously to any given flight or simulator research experiment.

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pilot-centered constraints are brought together in a way which can produce a meaningful basis of analysis. However, what confounds the execution of this procedure is a lack of quantification in some of the pilot-centered areas of control technique and perception. At the same time it is feasible to go after these needed measurements. This can be done over the long term using targets of opportunity or over a shorter term with deliberate, well-planned research programs involving both flight vehicles and simulators.

In laying out a rational approach to determination of training simulator fidelity requirements, one of the important byproducts is a unification of training literature which describes various piloting tasks and the established ideas of manual control theory. This unification is useful in describing and predicting pilot behavior given quantification of the task. These ideas, combined from the training and engineering communities, provide some interesting implications for both of these communities. For example it may be possible to enhance pilot training methods through use of some of the piloting technique measurement methods suggested. These are ways of describing how a pilot is carrying out a particular task as opposed to how well certain standards are met, i.e., it focuses on the mechanisms of performing a task. From the engineering point of view, the formalized lists of tasks and task descriptions which are presented in the training literature provide some useful views of how better to formulate design objectives, e.g., if the piloting task is sufficiently well defined, then it should be possible to develop clear rationale in areas such as aircraft flying qualities and performance.

## INTRODUCTION

### BACKGROUND

Design specification for training simulators involves answering questions such as: How much motion travel? — How good a visual scene? Much effort has been expended in trying to answer these questions with few definitive results,<sup>1</sup> yet economic pressure to use training simulators in place of actual flight training steadily increases.

Attention frequently focuses on simulator fidelity as being the culprit in many simulator training problems; but, as some have pointed out: "There is no compelling relationship between training effectiveness and fidelity/realism."<sup>2</sup> And to the extent that this is a true statement, we may want to be careful not to overdo realism aspects. As AGARD Working Group 10 points out, the question of fidelity involves perceptual aspects; and requirements for these perceptual aspects are not well known with respect to training<sup>3</sup>. This is an area, therefore, which needs study. It

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<sup>1</sup> Adams, Gerald H., (Ed.), Flight Simulator Training. Volume 1: 1964-1973 (A Bibliography with Abstracts), NTIS/PS-77/0145, March 1977.

Habercom, Guy E., Jr., (Ed.), Flight Simulator Training. Volume 2: 1974-February 1980 (Citations from the NTIS Data Base), NTIS/PB80-806425, March 1980.

Anon., 50 Years of Flight Simulation. Conference Proceedings. Session 1 through 3, 1979.

Puig, Joseph A., William T. Harris, and Gilbert L. Ricard, Motion in Flight Simulation: An Annotated Bibliography, NAVTRAEQUIPCEN IH-298, July 1978.

<sup>2</sup> Eddowes, Edward E., and Wayne L. Waag, The Use of Simulators for Training In-Flight and Emergency Procedures, AGARD-AG-248, June 1980.

<sup>3</sup> Key, David L., (Ed.), Fidelity of Simulation for Pilot Training, AGARD Advisory Report No. 159, October 1980.

is of particular interest to focus on the issue of visual simulation fidelity in connection with the difficult training objectives involving nap-of-the-earth (NOE) operations<sup>4</sup>.

The Army Research Institute (ARI) Field Unit at Ft. Rucker, Alabama, is engaged in conducting flight simulator research in three areas:

1. Requirements — the definition of training device requirements to meet the training objectives with emphasis on visual and motion systems.
2. Evaluations/Validation — in terms of training transfer, does the flight simulator meet its design goals? Further, do the visual systems provide sufficient information to train the Army mission?
3. Utilization — research is in progress to determine the training effectiveness of the Army's synthetic flight training system (SFTS).

In recent years, the Ft. Rucker Field Unit has been engaged in near-term research to answer some questions in the three categories defined above. In some cases, information is not sufficient to provide complete and accurate answers, particularly in the areas of visual and motion system fidelity.

In order to approach training simulator fidelity in a rational way, it is necessary to develop some cause and effect relationships. For example: How does the pilot respond to stimuli, What happens to the aircraft, and How is the task carried out? For the most part simulator

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<sup>4</sup> Roscoe, Stanley N., Halim Ozkaptan, and Aaron Hyman, Review of Flight Training Technology, U. S. Army Research Problem Review 76-3, July 1976.

Gainer, Charles A., and Dennis J. Sullivan, Aircrew Training Requirements for Nap-of-the-Earth Flight, U. S. Army Research Report 1190, August 1976.

training literature<sup>5</sup> does not concentrate on piloting strategy or technique, rather on systems performance (scoring, tracking dispersions, success/failure). Without an understanding of the pilot's actions, we are dealing with a distinctly closed-loop system on an open-loop basis, that is to say, we know just the command and the final response. But this limited knowledge of the command and the response confounds the analysis of the factors affecting pilot actions.

There are, however, established methods for dealing with the mechanisms of pilot behavior, especially on a psychomotor level. McRuer and Krendel<sup>6</sup> outline a theory of manual control which gives a rationale for how a pilot operates, adjusts, and fits into an overall pilot-vehicle relationship. Various approaches to this theory include not only classical but also modern control theory techniques. Also there is an existing manual control theory data base, although it is somewhat limited in terms of completeness of piloting task. Thus there is a role for control theory in formulating a complete picture of the pilot in the loop.

#### OBJECTIVES AND SCOPE

In view of the background outlined above and especially the motivation provided by AGARD Working Group 10<sup>7</sup>, the objectives of this study are to identify simulator requirements for training by using available data on motion and visual senses in combination with manual control theory. There will be no original data collection involved; rather, a review of the

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<sup>5</sup> Adams, 1977, op cit.

Habercom, 1980, op cit.

<sup>6</sup> McRuer, D. T., and E. S. Krendel, Mathematical Models of Human Pilot Behavior, AGARD-AG-188, January 1974.

<sup>7</sup> Key, 1980, op cit.

literature and an expression of a methodology for addressing simulator requirements will be presented. The specific tasks to be addressed in this study include:

1. Definition of the term "simulator fidelity" and development of a taxonomy of measurable parameters of simulator fidelity.
2. Development of procedure for analytically determining the type and quality of visual and motion cues required to train flight skills in a simulator
3. Development of a methodology to define visual and motion cue requirements by training objectives
4. Determination of commonality among training objectives in terms of fidelity requirements for visual and motion systems
5. Recommendations for research to acquire additional empirical data where it is deemed to be necessary.

The scope of this study includes a full range of Army aircraft including fixed-wing and helicopters, skill levels from undergraduate through continuation training, both instrument and visual meteorological conditions, and a variety of tasks including the critical scenarios involving NOE, and weapon delivery.

#### **TECHNICAL APPROACH**

The technical approach applied to this project is reflected by the specific organization of this report. We begin by defining simulator fidelity in operational terms which provides a basis for each of the subsequent steps. This definition is accompanied by a taxonomy of measurable fidelity parameters. The next step, also of a preparatory nature, is the analysis of Army flight training missions. Here we describe how specific flight tasks and piloting techniques can be cast in terms compatible with

feedback control theory. Pilot modeling techniques are then discussed, first in terms of pilot control and then in terms of pilot perception. Next, armed with compatible descriptions of fidelity, the training context, and pilot behavior, we describe a procedure for studying visual and motion stimuli. Finding that there are serious gaps in the basic experimental data, however, prevents the systematic execution of this procedure. Thus, because of the lack of experimental data, we outline a formal bookkeeping scheme to guide our investigation of fidelity requirements. This leads us finally to a discussion of the kind of research needed and the applicable measurement methods for defining fidelity requirements. Conclusions and recommendations are then drawn. As aids to the reader, an executive summary and a glossary of terms are provided.

The means to achieving the previously listed objectives is to apply established data on human operator behavior, aircraft response, sensory perception, and piloting technique with regard to the issues of simulator fidelity and pilot training. A new area to be addressed consists of the definition of piloting task (training objective) in terms which are compatible with the quantification of the pilot-vehicle system.

Because of the potential complexity due to the compounding effects of several components (tasks, piloting technique, piloting perception, aircraft model, and simulator response) it is desirable to minimize the complexity of each of these components; but simplification is a worthwhile goal, anyway, since it helps to isolate and emphasize the very important parameters and features. Fortunately there are many examples which help to show the way for system simplification.

A key feature of the technical approach is to acknowledge the bounds and constraints imposed by the physics of the vehicles, the physiology of the pilot sensors, and by the rules and criteria of control theory (controllability, response, bandwidth, stability, settling time, etc.). This greatly aids in understanding what is important or essential to training. In fact, a major objective of the technical approach is to identify the essential behavior in terms of essential loops and the corresponding essential cues which support these loops.



## DEFINITION OF SIMULATOR FIDELITY

This section addresses the topic of simulator fidelity in two steps:

- First, definition of simulator fidelity in a manner which is useful for the determination of motion and visual system characteristics necessary for flight training.
- Second, translation of this definition of fidelity into a taxonomy of measurable fidelity parameters.

These two steps, taken together, provide the basis of the subsequent final report topics.

The underlying approach used in the execution of this entire effort is to formulate simulator requirements using a combination of (a) manual control theory, (b) knowledge of human perceptual mechanisms, (c) definitions of specific Army flight missions and tasks, and (d) conventional engineering mathematical models of simulator components. The unifying element will be the use of compatible mathematical terms for each of these four components.

With regard to fidelity, we shall begin by reviewing some current notions of fidelity which, in turn, will be incorporated into a special definition of fidelity suited to our approach. This definition will then lead us to consider parameters which are explicitly related to fidelity. It will be noted that these parameters are fundamentally separate from the more implicit fidelity parameters commonly used to specify simulator system requirements. We will thus distinguish between "explicit" and "implicit" fidelity in this section.

The strength of the approach to be applied to simulator fidelity requirements is its potential to cover many diverse flight tasks and environments, various stages of skill development, and the several modalities used by the pilot. The approach can provide rational answers to

questions of simulator fidelity where there is adequate quantification of critical elements, and it can aid in identifying where there are gaps in such quantification.

Finally, before taking up the matter of simulator fidelity, the following ideas are offered for prefatory consideration. Each of these notions which plays a role in fidelity will be further discussed and developed in the sections to follow.

- Transfer of training from simulator to flight can be enhanced by identifying the pilot's organization of perception and technique in flying tasks and by similar organization of perception and behavior in the simulator.
- The task objective, the dynamics of a vehicle, and the realities of the environment dictate the behavior of the pilot and organization of perception.
- Cognitive processes determine what is desired or required by the pilot to accomplish the task objective.
- Psychomotor and cognitive actions tend to be a comparison of what is with what is desired followed by a commensurate action to achieve the desired.
- The control strategy and technique of the pilot is induced by the dynamics of the vehicle being controlled. The actual aircraft is the baseline vehicle — the simulator is to some degree a distortion of the aircraft and the environment.
- The pilot reacts to the dynamics of the vehicle only if they are detectable.
- Training manual task descriptions and standards along with descriptions by skilled pilots can be interpreted as mathematical control laws.
- Training is manifest by a successive organization of perception and the evolution of control strategy in pilot technique. It requires formulation of pilot objectives, detection of dynamic quantities, and appropriate action of controls.

## AN OPERATIONAL DEFINITION

### Some Notions of Fidelity

Any consideration of fidelity connected with the acquisition of a simulator system has, in the past, focused more on what the simulator does than how the pilot responds. This is understandable since the mechanical, electrical, and computational specifications must ultimately be defined for the simulator fabricator. Unfortunately there is nothing in such specifications, even if providing adequate fidelity in one simulator, that would guarantee the same degree of fidelity in another. It is widely accepted that the adequacy of a simulator is highly conditional upon vehicle type, flight task, flight environment, and pilot skill level. Such conditionality, in practice, generally precludes the simple extrapolation of simulator fidelity requirements from one system to another.

The first step of this study is to derive a working definition of simulator fidelity which will serve as a basis for quantification of fidelity parameters. This can be accomplished by refining and expanding some existing notions regarding fidelity. More specifically, we shall show how some perceptual and behavioral aspects can be quantified for the purposes of specification.

We shall begin by considering some simulator fidelity ideas which are useful for our purposes. The AGARD Working Group 10<sup>8</sup> presents a discussion of fidelity which distinguishes two main "types" of fidelity: objective fidelity and perceptual fidelity.

Objective fidelity (or, perhaps more precisely, engineering fidelity<sup>9</sup>) is the degree to which the simulator reproduces measurable aircraft states or conditions. In terms of motion fidelity, perfect engineering fidelity

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<sup>8</sup> Key, Ibid.

<sup>9</sup> Sinacori, John B., Piloted Aircraft Simulation Concepts and Overview, NASA CR-152200, March 1978.

would correspond to a one-to-one duplication of inertial-based displacements, velocities, and accelerations in each axis of freedom.

Perceptual fidelity is the degree to which subjects perceive the simulator to duplicate aircraft states or conditions. This type of fidelity is pilot-centered and includes both psychological and physiological effects. We shall not, however, concede that perceptual fidelity is either unmeasurable or unquantifiable. In fact, our technical approach is based largely upon ultimately quantifying or describing how to quantify perceptual effects.

To the extent that the human operator's perception can be explained in rational terms, it is possible to merge the ideas of engineering and perceptual fidelity. For example, since the human vestibular system can be described in terms of effective washouts, lags, and thresholds, then it is possible to apply the same objective engineering metrics as one does to a mechanical motion base platform, an electrical network, or an airplane equation of motion. We shall develop this idea shortly.

Another aspect of fidelity which needs to be addressed is that of induced pilot control strategy and technique. A recently convened NASA Advisory Subcommittee<sup>10</sup> defines simulator fidelity as the adequacy of perceptual effects and their consequent pilot response behavior [i.e., control strategy and technique] induced by the simulator. Furthermore this is attached to a specified task environment. The issue of control strategy and technique is, of course, central to learning and skill development. If the simulator cannot induce correct technique, then its role in training is questionable. At the very least, failure of a simulator to induce certain features of correct technique should be duly noted.

It is further suggested that the pilot response induced by a training simulator for a given task should normally include the errors committed

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<sup>10</sup> Ad Hoc Advisory Subcommittee, Avionics, Control and Human Factors.

while learning to perform the task in the aircraft. Carter<sup>11</sup> suggests the use of the term "error fidelity" to formalize the idea of evaluating the fidelity of a simulator for a specific task in terms of the similarity between the errors occurring in the simulator and those occurring in the aircraft. This concept appears to provide an additional framework for the systematic determination of fidelity requirements which has not been explored in past studies. According to this concept a simulator has high error fidelity for a given task when:

1. Students tend to make the same errors in the simulator that they make when learning the same task in the aircraft.
2. The relative frequency of the different errors associated with the task in the simulator is approximately the same as in the aircraft.
3. The effect of each student error on system performance, flight path, and maneuver outcome in the simulator is the same as in the aircraft.

Error fidelity can have a very significant impact on transfer of training. Student errors which do not have the same effect on system performance and maneuver outcome in the simulator as they do in the aircraft can lead to serious negative transfer of training. For example, a student control error which would cause the aircraft to depart from controlled flight and result in an undesirable maneuver outcome in the aircraft must be made to have the same effect in the simulator. Error fidelity thus represents an important simulator design goal.

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<sup>11</sup> Carter, V. E., and C. A. Semple, Specific Behavioral Objectives for VF-121 Training in Basic Air Combat Maneuvers. Volume 3, (CONFIDENTIAL), NOR 76-52, March 1976.

## An Overview of the Pilot in the Simulator

We have mentioned several aspects of fidelity including:

- Objective fidelity
- Perceptual fidelity
- Induced pilot control strategy and technique
- Error fidelity

Our approach is to quantify each of the above to the extent possible and to form a model of the combined pilot-simulator which can then be compared to a like model of the combined pilot-aircraft. We shall explain this approach in several steps.

First, consider the diagram of a typical training simulator apparatus as depicted in Fig. 1. Three main components are shown, the digital computer, the visual field synthesizer, and the cab. Inside the cab the pilot is provided with information based on motion, instruments, audio, and outside visual scene. Pilot behavior is then manifested by control actions, which feed back to the computer. Setting the pilot aside, all the components in Fig. 1 have widely accepted means of quantification. That is, the so-called engineering fidelity of each can be stated in reasonably direct terms. In fact, such terms form some of the commonly used fidelity parameters which are used to specify system performance.

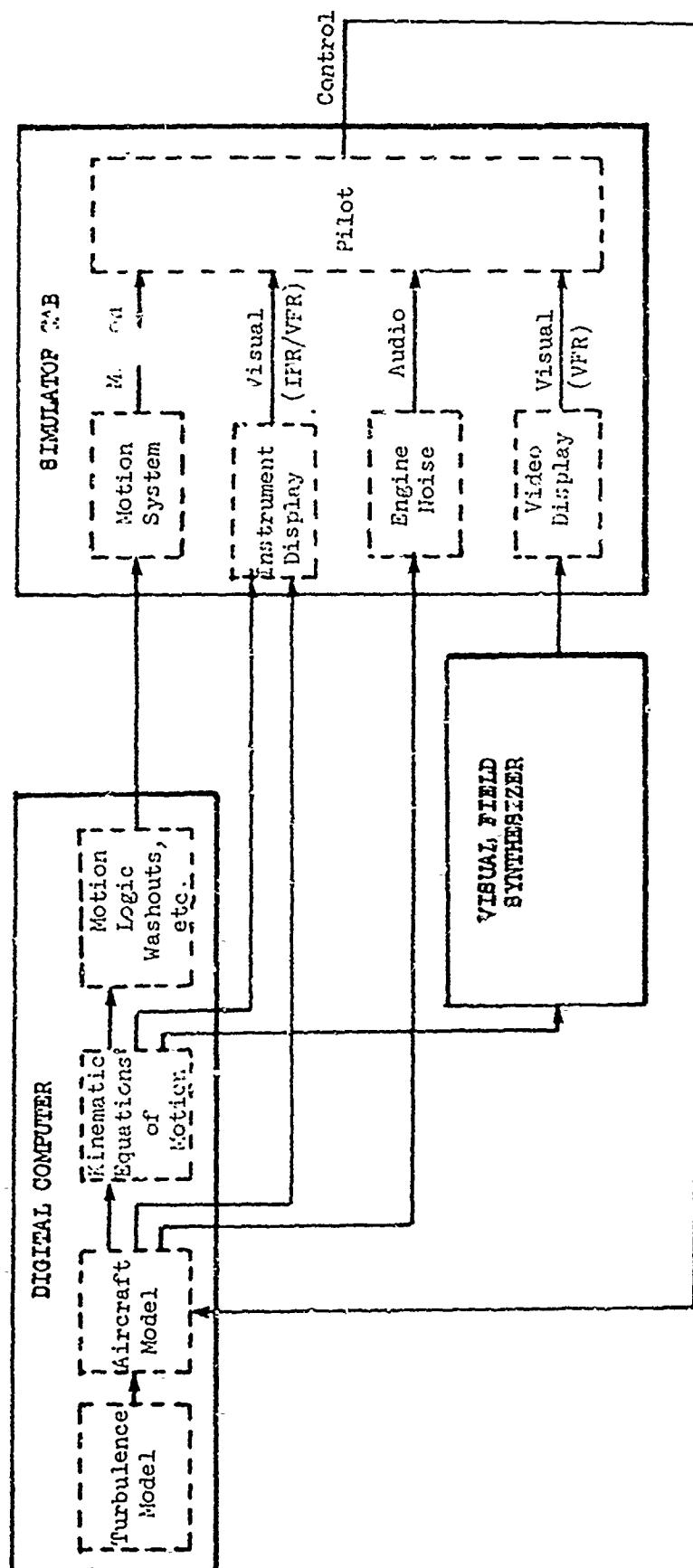


Figure 1. Typical Training Simulator Apparatus

Relevant training simulator examples include the Army's UH-1 requirement document<sup>12</sup> and UH-60 specification<sup>13</sup>.

The key to providing a more wholly rational scheme of expressing fidelity depends on how we address the block labeled "pilot" in Fig. 1. This is, in fact, precisely the matter of handling perceptual and induced behavior aspects of fidelity.

Induced pilot behavior consists of making adjustments in piloting technique within a given overall structure of piloting technique. The adjustments can consist of loosening or tightening-up the regulation of flight parameters (attitude, airspeed, etc.), making gentle or aggressive maneuvers, and making use of the learned response of the aircraft by employing increasingly more precognitive control actions. A convenient means of viewing the adjustment of pilot behavior is outlined by McRuer and Krendel<sup>14</sup>. Based on substantial experimental research, rules for pilot psychomotor behavior are expressed in terms which are compatible with the "controlled element" — the simulator or the actual aircraft, as the case may be. We shall cover this more thoroughly in the section on pilot modeling, but it is useful to present some overview at this point.

Figure 2 shows an expanded pilot block and labels it as a "structural isomorphic model." That is to say that each important functional aspect of the pilot is accounted for in the model. Functions include the sensory (perceptual) mechanisms, the central elements (cerebrospinal system), neuromuscular actuation system, and the controlled element (parts of the aircraft which are closely tied to the human operator dynamics such as the cockpit manipulators). It is important to note that, having considered

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<sup>12</sup> Radder, Preston W., Capt., Department of the Army Approved Qualitative Materiel Requirement (QMR) for a Synthetic Flight Training System (SFTS) (Rotary Wing), 28 August 1972.

<sup>13</sup> Schalow, P. S., Specification for UTTAS Helicopter Synthetic Flight Training System, Device 2B38, Naval Training Equipment Center Report No. 2222-1152, 30 October 1975.

<sup>14</sup> McRuer and Krendel, 1974, op cit.



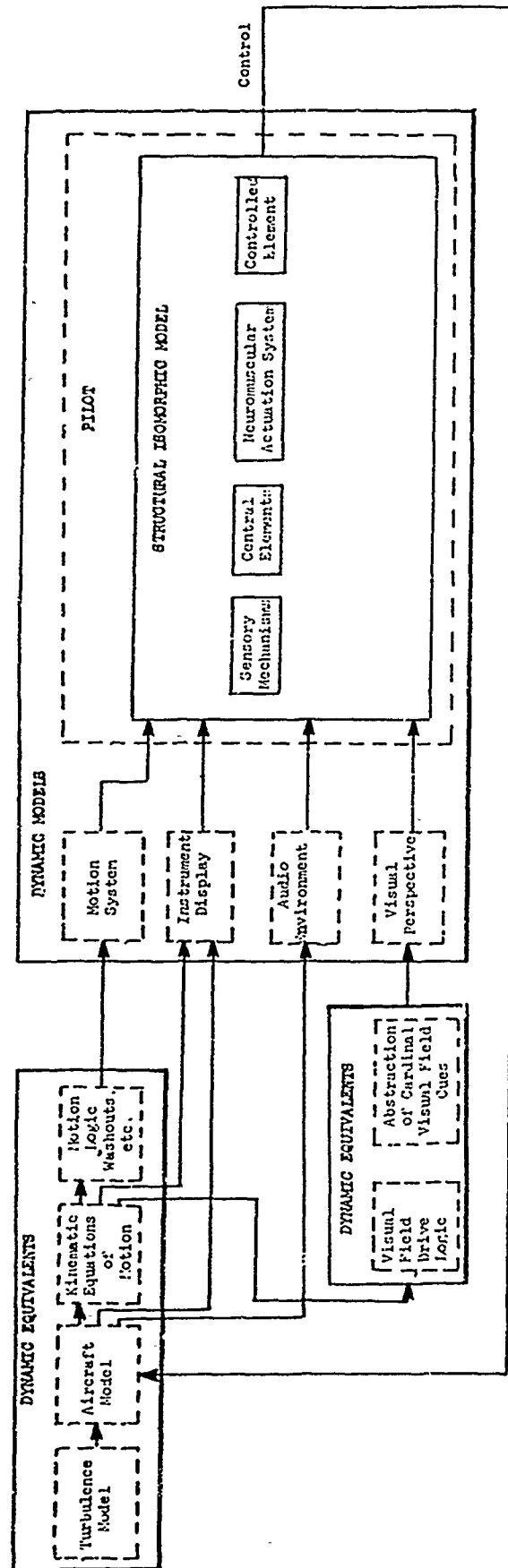


Figure 2. Typical Representation of Simulator Apparatus  
For the Purpose of Fidelity Analysis

the structural isomorphic model, we are able to reduce its complexity to a lower level by using an effective system pilot model.

The specific structure of the piloting technique used to carry out a given task is already well established. That is, there are prescribed functions for each aircraft control and these functions are conveyed to trainees at an early stage by instructors and by training manuals. We shall rely heavily on the latter medium in order to construct formal analytic models of piloting technique appropriate for each training objective. An example of this is given in the section to follow.

The modeling of perception requires consideration of sensory dynamics, cerebral processing of sensor information, and division of attention among multiple sensors and sensor channels. In the following discussions, however, we shall limit ourselves to the first two aspects.

Human perceptual mechanisms and their dynamics have been described in a number of sources. The motion perception models described by Ormsby<sup>15</sup> are convenient and adequate for our purposes. A number of sources go on to deal with how motion perception is used in the performance of certain basic task components.<sup>16</sup> Visual perception is more complicated, however. Hennessy, et al.,<sup>17</sup> describes in considerable detail the many dimensions of visual perception and emphasizes its importance in simulator fidelity research topics. But visual perception can also be handled in ways compatible with our closed-loop approach. Namely, visual perception may be quantified and tied directly to pilot behavior during specific

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- 15 Ormsby, C. C., Model of Human Dynamic Orientation, MIT Ph.D. Thesis, January 1974.
  - 16 Hofmann, L. G., and Susan A. Riedel, Manned Engineering Flight Simulation Validation. Part I: Simulation Requirements and Simulator Motion System Performance, AFFDL-TR-78-192, February 1979.
  - 17 Hennessy, Robert T., Dennis J. Sullivan, and Herbert D. Cooles, Critical Research Issues and Visual System Requirements for a V/STOL Research Simulator, Canyon Research Group, Inc., Final Technical Report No. RTH-0180, 40-3053, 14 June 1979.

tasks<sup>18</sup>. Additional background and insights into visual perception, its measurement, and its modeling will be discussed in the section on pilot modeling; but Table 1 gives several examples of how motion and visual perceptual mechanisms can be modeled for use in determining simulator fidelity.

An additional fidelity notion we shall mention at this point is that of pilot model adjustment based on vehicle dynamics. According to manual control theory<sup>19</sup>, the pilot tends to adapt his control behavior in a way which complements the dynamics of the vehicle — simulator or aircraft. The specific rules for adaptation are reasonably well understood and have been verified experimentally on many occasions. We shall dwell upon this matter also in a subsequent section.

For now, however, we would propose that one measure of fidelity is how well the simulator induces pilot control adaptation suitable for the actual aircraft. This would be evident from direct measurement of features involved in the pilot model and by analytically comparing features so measured in a simulator to features so measured in an actual aircraft as shown in Fig. 3 (for motion stimuli) and Fig. 4 (for visual stimuli). There are several techniques available for measuring pilot psychomotor behavior. A general discussion of these techniques is given

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<sup>18</sup> Sinacori, 1978, op cit.

Clement, Warren F., Robert K. Heffley, and Wayne F. Jewell, Field-of-View Requirements for Approach and Landing of V/STOL Aircraft, NADC 77240-07, August 1978.

Heffley, Robert K., "A Model for Manual Decelerating Approaches to Hover," Proceedings of the Fifteenth Annual Conference on Manual Control, AFFDL-TR-79-3134, 1979, pp. 545-554.

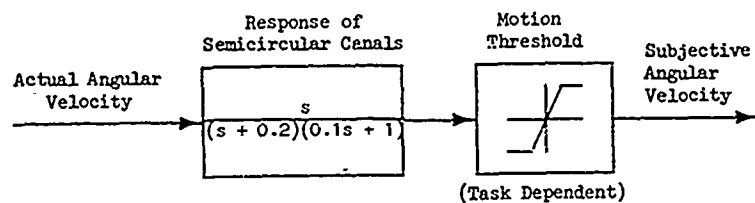
Heffley, R. K., T. M. Schulman, R. J. Randle, Jr., and Warren F. Clement, Analysis of Airline Landing Data Comparing Pilot Training in a Simulator Versus Actual Flight, Forthcoming NASA Technical Memorandum, 1981.

<sup>19</sup> McRuer and Krendel, 1974, op cit.

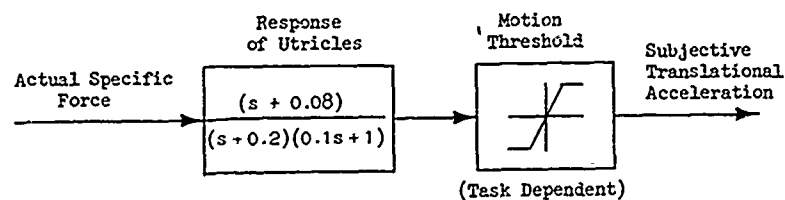
TABLE 1

EXAMPLES OF MOTION AND VISUAL PERCEPTION FUNCTIONS

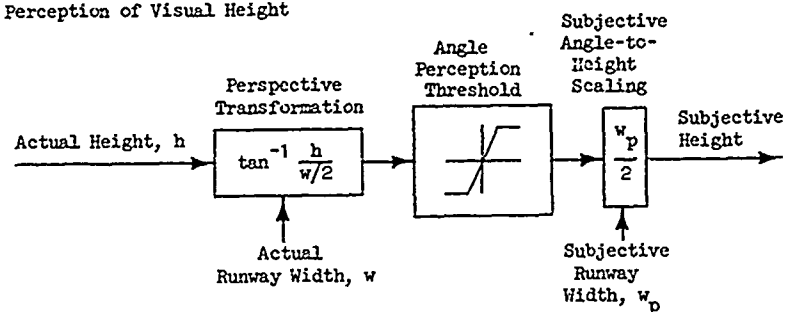
• Perception of Rotational Motion<sup>20</sup>



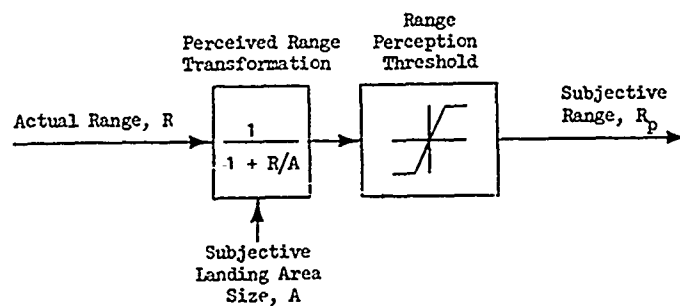
• Perception of Translational Motion<sup>21</sup>



• Perception of Visual Height



• Perception of Visual Range<sup>22</sup>



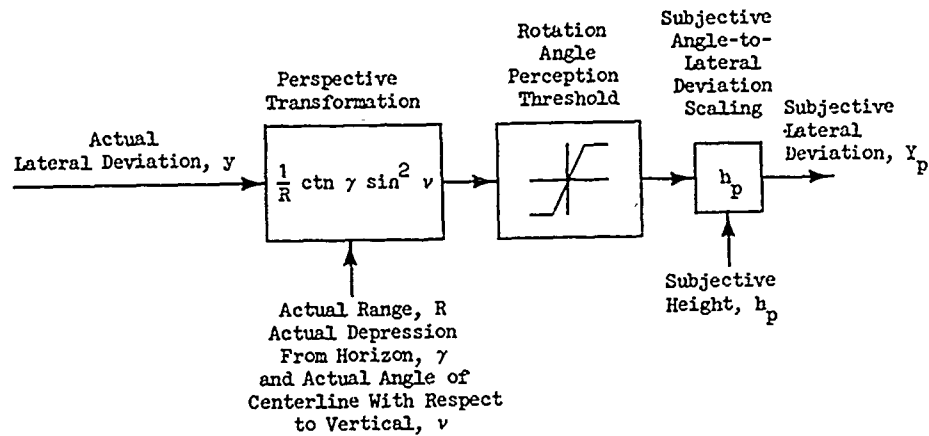
<sup>20</sup> Hofmann and Riedel, 1979, op cit.

<sup>21</sup> Ibid.

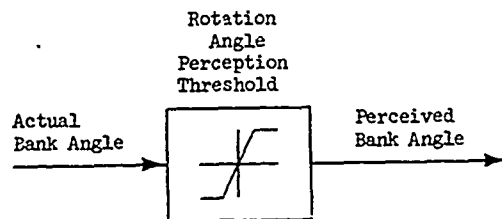
<sup>22</sup> Heffley, 1979, op cit.

TABLE 1 (Concluded)

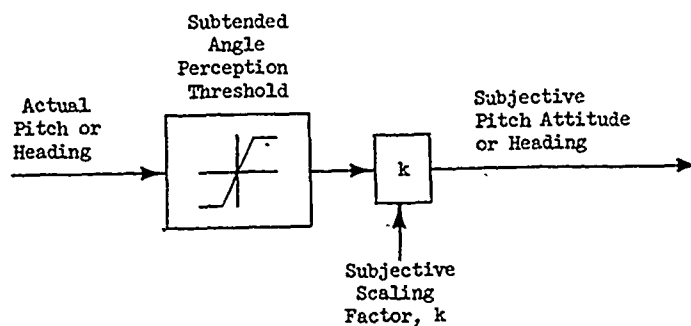
● Perception of Visual Lateral Deviation<sup>23</sup>



● Perception of Visual Bank Angle



● Perception of Visual Pitch Attitude or Heading



<sup>23</sup> Clement, Heffley, and Jewell, 1978, op cit.

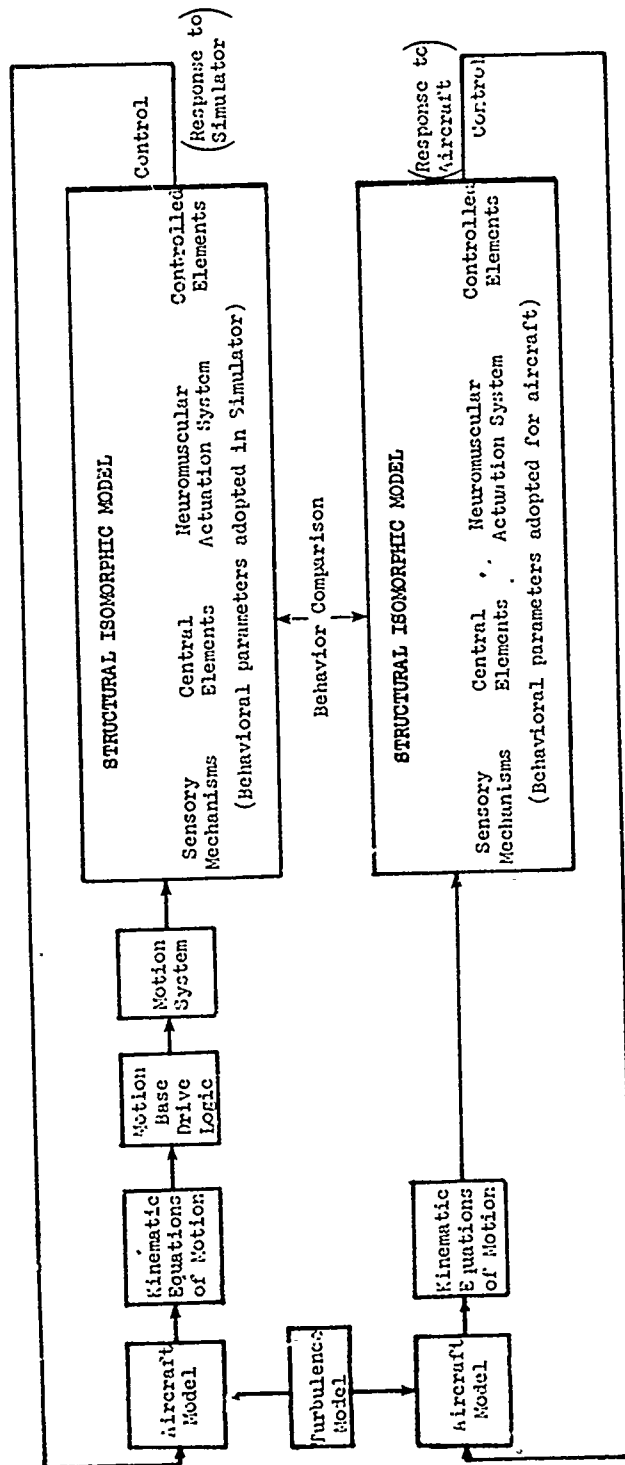


Figure 3. Comparison of Behavioral Parameters Adopted For Motion Drive Logic to Those Adopted for Aircraft

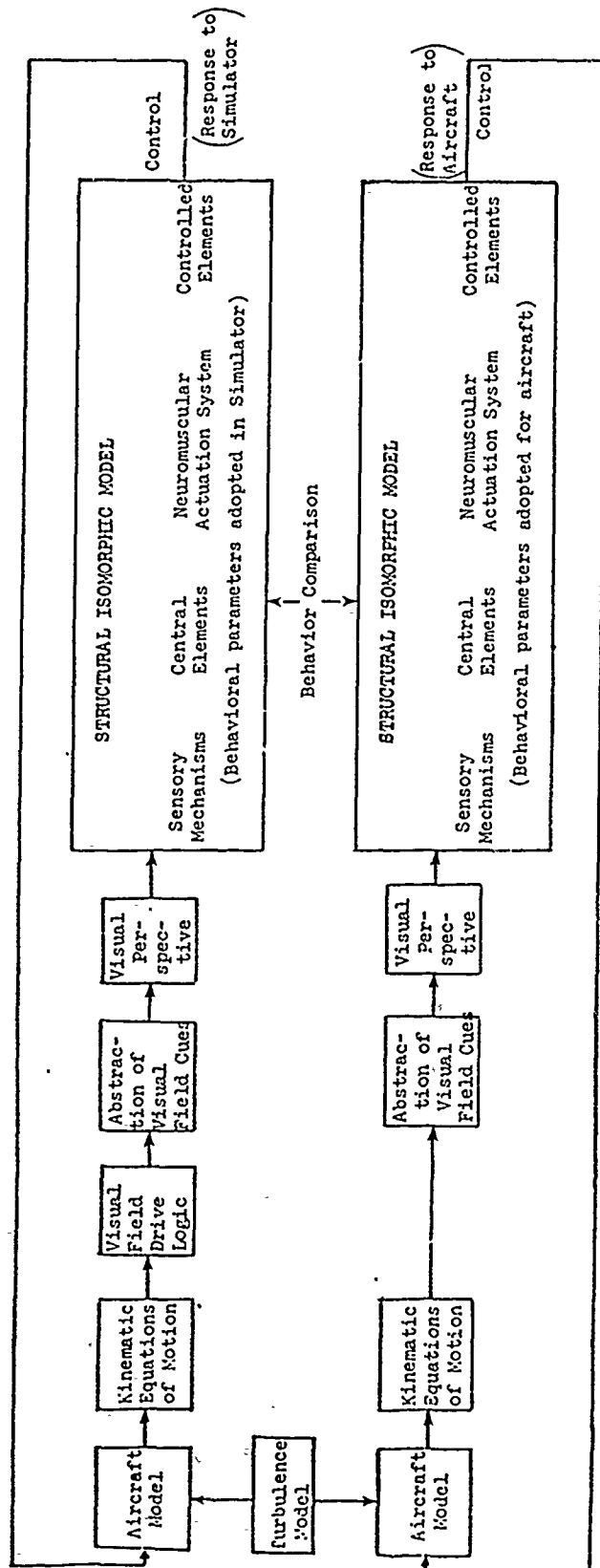


Figure 4. Comparison of Behavioral Parameters Adopted For Visual Field Drive Logic to Those Adopted for Aircraft

by Clement<sup>24</sup> and will be specialized more to our needs later in this report.

It should be pointed out that a large body of literature already exists in which pilot measurements have been made for specific elements of many tasks. A portion of this material has been compiled and will be presented in the next section. Some cases considered address relatively complete piloting tasks.

### **Statement of An Operational Definition of Fidelity**

We have arrived at a point at which it is possible to set forth a general definition of simulator fidelity which takes advantage of our growing knowledge of the pilot's perceptual mechanisms, strategy, and technique induced by the simulator, the dynamics of the simulator components (electro-mechanical and electronic), and the specific flight tasks of interest.

Note that the means of viewing the simulator and the pilot, which is described above, allows for extensive and direct quantification. Our objective regarding fidelity is to establish a working definition which takes full advantage of such quantification.

Consider also that training is the development and refinement of a suitable control loop structure — the specific means by which a task is carried out. Further, training involves teaching the student to use perceptual mechanisms appropriate to the given task.

Therefore an appealing approach to simulator fidelity is to focus on how the pilot carries out a particular task given the perception (or

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<sup>24</sup> Clement, Warren F., Robert K. Heffley, Wayne F. Jewell, and Duane T. McRuer, Technical Approaches for Measurement of Human Errors. Final Report, Systems Technology, Inc., Technical Report No. 1156-2, July 1980.



inferred perception) of necessary cues. Hence we would construct a quantitative comparison between simulator and the actual flight situation of the combined induced strategy and pilot perception. This frees us from the notion that perfect fidelity is a one-to-one correspondence between simulator systems and the actual aircraft<sup>25</sup> — a practical impossibility anyway. Rather, perfect fidelity is characterized by the simulator pilot behaving in a manner appropriate to the aircraft situation. These ideas do not, in essence, vary from the various concepts of simulator fidelity mentioned earlier.

We suggest, then, that fidelity is the specific quality of a simulator that permits the skilled pilot to perform a given task in the same way that it is performed in the actual aircraft. Execution of said task is simply the closure of all loops made necessary by both the task requirements and the dynamics of the vehicle and subject to the information which is available. In order to close loops on the required states, cues corresponding to the states themselves must at least be defined, perceived, and recognized in terms of essential cardinal abstractions from the pilot's perceptual fields, here limited to visual and vestibular. That cues must be defined, perceived, and recognized implies first the requirements that:

- The task variables have been defined for the pilot. Task variables include the specific purposes, assignments, and commands comprising the mission strategy, the likely guidance media, the vehicle to be used, and the likely disturbances and counteractions to be expected throughout the mission profile. Task variables comprise all the system inputs and those vehicular elements external to the pilot which enter directly and explicitly into the pilot's assignment.

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<sup>25</sup> This notion follows from the identical elements theory of transfer of Thorndike.

Second, this implies the requirement that:

- The feedback (and feedforward) cues essential to the task can be (a) employed by the pilot and (b) discovered by the analyst. These cues are called "essential feedbacks"<sup>26</sup>. The feedback cues actually selected by the pilot will correspond to the states which are both necessary and sufficient to satisfy the guidance and control needs and certain pilot-centered requirements.

The guidance and control needs are situation specific. Satisfaction of these needs always involves the organization of perception and adoption of task-centered outer loops, with the addition of subsidiary inner loops and other axis crossfeeds as needed to promote the adoption of the outer loops in accord with the following pilot-centered requirements<sup>27</sup>. The feedback loops preferred are those which<sup>28</sup>:

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<sup>26</sup> McRuer, Duane, Irving Ashkenas, and Dunstan Graham, Aircraft Dynamics and Automatic Control, Princeton University Press, Princeton, New Jersey, 1973.

<sup>27</sup> The Successive Organization of Perception (SOP) theory of skill development is treated in McRuer and Krendel, 1974, op cit.

Krendel, E. S. and D. T. McRuer, "A Servomechanisms Approach to Skill Development," Journal of the Franklin Institute, 269, 1960, pp. 24-42.

McRuer, Duane T., Warren F. Clement, and R. Wade Allen, A Theory of Human Error, Systems Technology, Inc., Technical Report No. 1156-1, May 1980.

Sheridan has attributed the cognitive organizing activities represented by SOP to a functional construct called the "metacontroller" within the cerebrospinal portion of the nervous system in Sheridan, T. B., "The Human Operator in Control Instrumentation," in R. H. Macmillan, et al., (Eds.), Progress in Control Engineering, Academic Press, New York, 1962, pp. 141-187.

<sup>28</sup> McRuer and Krendel, 1974, op cit.

1. Can be closed with pure gain equalization by the pilot.
2. Can tolerate a time delay which is characteristic of the appropriate modality.
3. Require the least scanning activity to perceive the feedback cue.
4. Permit great latitude in the pilot's adopted characteristics.

Third, this implies the requirement that:

- The cues corresponding to the essential feedbacks should be represented by coherent patterns<sup>29</sup> in the perceptual fields which the pilot has learned (or will learn) to recognize in flight. Each intrinsic pattern, in turn, must be sufficiently coherent in situ to exceed the pilot's threshold of recognition.

Fourth, this implies the requirement that:

- The cardinal features which comprise the patterns should present a perceived signal-to-noise ratio to which the pilot is (or will be) accustomed in flight.

Given the perceptual abilities of the pilot, there are four additional requirements regarding dynamic changes in cues corresponding to dynamic changes in the essential feedbacks. The change in cues or states must:

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<sup>29</sup> Such coherent patterns have been called cardinal cues, abstractions, or features. Examples are discussed in Ibid.

Clement, Field-of-View Requirements for Approach and Landing of V/STOL Aircraft, 1978, op cit.

Gilinsky, A. S., "Perceived Size and Distance in Visual Space," Psychological Review, 58, 1951, pp. 460-482.

Gilinsky, A. S., "The Effect of Attitude Upon the Perception of Size," American Journal of Psychology, 68, 1955, pp. 173-192.

Hennessey, 1979, op cit.; as well as the bibliography appended hereto.

- Be large enough to exceed the perceptual thresholds (e.g., vestibular thresholds or visual acuity)
- Be quick enough to permit the closed loop bandwidths required (e.g., motion lags or visual update)
- Be sufficiently distortion free to permit correct compensation by pilot (e.g., washout not too fast, ...)
- Be sufficiently noise free as not to require workload for processing, filtering, or reconstructing patterns of change (e.g., motion vibration level, picture jitter or flicker should be minimized)

Hence we have tied fidelity directly to the pilot's use of perceived states. The perceived states, in turn, can be characterized in terms of:

Threshold

Quickness

Distortion

Signal-to-noise ratio

Each of these characteristics is, in turn, directly quantifiable in a variety of ways. For example, motion threshold is directly related to thresholds of the human vestibular system. Such thresholds, although somewhat task dependent, are nevertheless well researched quantities. Quickness is most likely tied to the control bandwidth required for a given task (e.g., pitch attitude usually involves a 1 to 2 rad/sec bandwidth). Distortion may be as simple as specifying flatness of frequency response which implies that the amplitude and shape of response are adequate. Finally, signal-to-noise ratio relates to ease of detection and can be established on an empirical basis. These four characteristics provide a basis for tying together the notions of engineering fidelity and perceptual fidelity.

It is important to recognize that the above concept of fidelity is based simply on the consideration of usable cues for a specific task. It is founded on the notion that pilot behavior and perception can be characterized in terms which are compatible with the simulator on one hand and the actual aircraft on the other. A summary definition of simulator fidelity is given in Table 2.

Let us now proceed to categorize quantifiable parameters which correspond to the above characteristics of fidelity.

## A TAXONOMY OF MEASURABLE FIDELITY PARAMETERS

### General Classification Scheme

In order to obtain the objectives of this study it is necessary to express the working definition of fidelity in terms of measurable fidelity parameters. In effect, we must encompass the notions of perceptual fidelity and induced pilot behavior into objective fidelity parameters.

The following is a taxonomy of fidelity parameters that is sufficiently general to incorporate previously developed fidelity metrics along with those that must be used to extend perceptual and behavioral aspects of fidelity.

The major components of our taxonomy include:

- States
- Transfer relationships
- Domains in which the above are expressed

The term "state" refers to a specific variable or dimension which is quantifiable in the usual sense. Common aircraft states, for example, could

TABLE 2

A SUMMARY DEFINITION OF SIMULATOR FIDELITY

**SIMULATOR FIDELITY:**

The degree to which *characteristics* of perceivable *states* induce *correct* psychomotor and cognitive control strategy for a given task and environment.

**WHEREIN:**

*Correct* strategy is locally defined in the training environment.

Applicable *states* are chosen on the basis of specified loop structure essential for the task.

*Characteristics* of states are determined by their role in inducing correct control technique (as defined in the training environment); i.e., quantification of loop structure adjustments (tightness, compensation).

Several domains can be used to express characteristics of applicable states in terms of convenient fidelity parameters.

The ultimate proof of training simulator fidelity is reflected in terms of transfer of training.

include attitude, airspeed, altitude, heading, and track along with their respective longitudinal and lateral-directional controls. "Transfer relationships" between states and pilot responses describe, among other things, how perceived states or "cues" issue from actual states and how control actions vary with perceived states<sup>30</sup>. Characteristics of transfer relationships include thresholds, quickness of response, distortion of response, and noise characteristics. Finally, the "domains" in which the states and transfer relationships could be expressed include temporal, frequency, or statistical domains. We shall develop these explanations further, but let us continue with a few more general comments on fidelity parameters.

One additional distinction we can make at this point is between "implicit" and "explicit" fidelity parameters. An implicit parameter carries a certain implied level of fidelity as a rather indirect or incidental consequence. An example might be pitching motion travel limits which, by themselves, do not guarantee an adequate level of motion to perform a particular task; yet without a given range of travel, motion fidelity could be a physical impossibility. The comprehensive simulator system specifications<sup>31</sup> are examples of implicit fidelity parameters. While they are admittedly necessary to construct a simulator, such implicit parameters do not, by themselves, convey or guarantee a level of fidelity. Explicit fidelity parameters, on the other hand, do address fidelity very directly because they characterize piloting technique and pilot perception with respect to relevant states and for a particular task. The approach to simulator fidelity taken by Hofmann and Riedel<sup>32</sup> deals with explicit

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30 Mathematically linear transfer relationships are called "transfer functions" of the complex operator,  $s = \sigma + j\omega$ . Quasi-linear approximations of nonlinear transfer relationships are called "describing functions" of the imaginary operator,  $j\omega$ , in the frequency domain.

31 Schalow, 1975, op cit.

32 Hofmann and Riedel, 1979, op cit.

fidelity parameters in that pilot perception is included in the analysis of simulator motion.

A concise way of illustrating the above ideas is given in Fig. 5 which shows a single loop comparison of pilot action in a simulator versus that in an actual aircraft. In each instance the input is pilot command and the output is perceived pilot response. The major task objective is keeping the two sets of pilot behavioral quantities matched. This characterization can apply to the psychomotor actions of maintaining attitude, airspeed, altitude, or to the more cognitive actions of tuning radios, setting flaps, and raising landing gear. Each of these actions would have its own loop quantification and could involve cross-coupling among various loops (subtasks).

Each of the blocks shown in Fig. 5 can be expressed mathematically. The most convenient means of expression is a frequency domain transfer function (or describing function).

The overall pilot-aircraft or pilot-simulator dynamics can be studied in either closed-loop or open-loop (i.e., the feedback loop artificially cut) terms. This provides a limited view of system performance. And because the pilot is a compensating element, it is likely that overall performance will appear to be similar between the aircraft and simulator. Not apparent are the fidelity aspects as reflected in the piloting technique and pilot perception elements. The point is: task performance, alone, does not indicate level of fidelity.

Implicit fidelity is represented mainly by the block labeled "simulator response" and, to an extent, by the "aircraft model." Both of these blocks are commonly included in the concepts of objective or engineering fidelity and may therefore be alternatively qualified as representing extrinsic fidelity.

Explicit fidelity includes the combination of "piloting technique" and "pilot perception." The level of explicit simulator fidelity is characterized by how well these blocks compare between the simulator and aircraft and may therefore be alternatively qualified as representing fidelity which is intrinsic to the training objective.



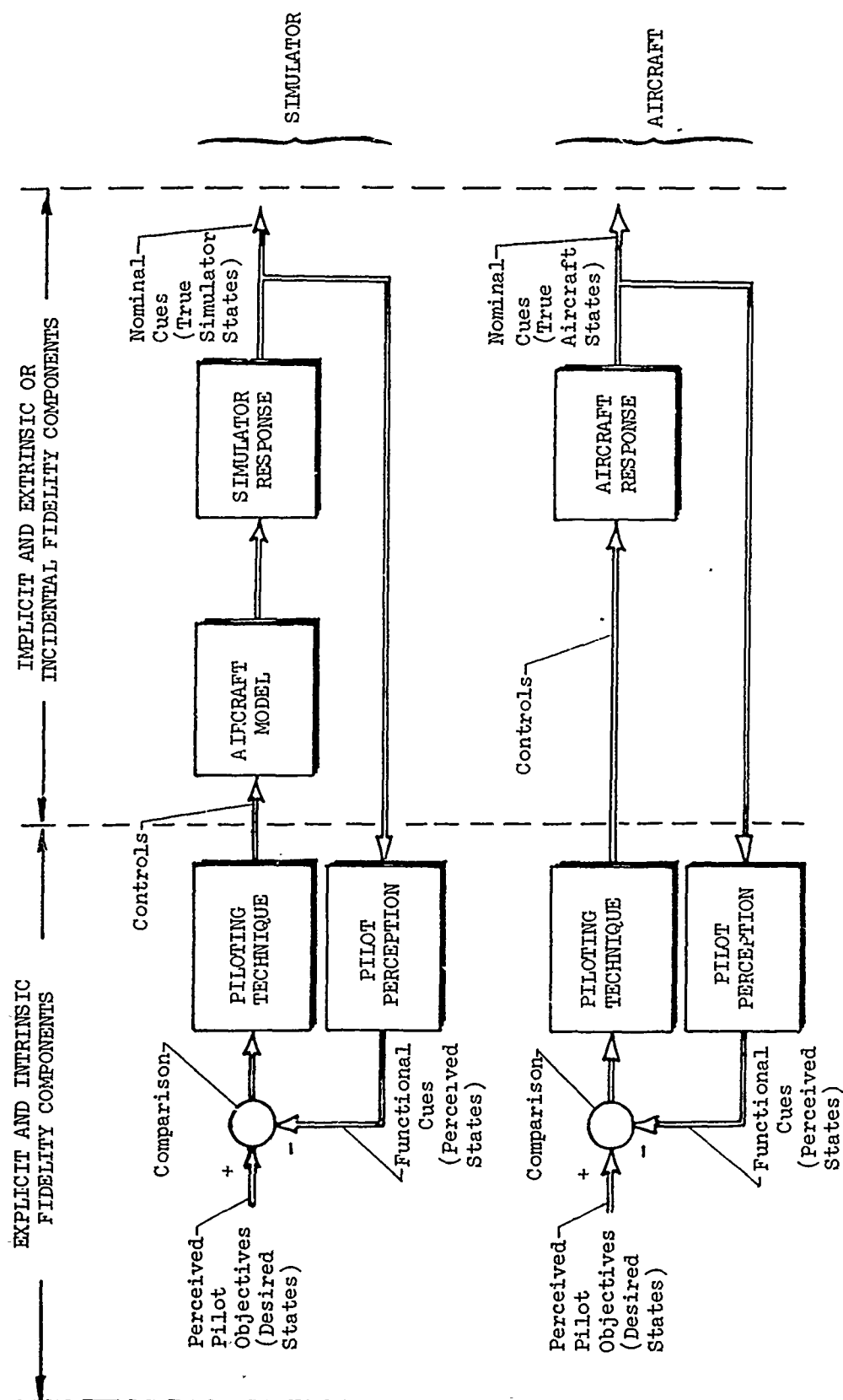


Figure 5. Components of Simulator Fidelity

## States

The term "state" refers to any of the variables which describe aircraft (or simulator) operation. This would naturally include attitude, heading, airspeed, altitude, angle of attack, engine torque, etc., along with various flight and engine controls. "State" could also refer to time derivatives or integrals of each variable above.

A list of fidelity-related states for both motion and visual modalities is summarized in Table 3.

The states which relate to fidelity are those which are involved in a particular mission phase or task. To find these states we would consider a block diagram of the piloting technique loop structure implied by, say, a training manual task description. Examples will be considered shortly.

## Transfer Functions Between States

Our term "transfer functions" can express the functional dependence of one state upon another and can include the implicit fidelity relationships of the simulator model and the simulator response (motion or visual). But more interesting are the transfer functions which describe pilot perception and pilot behavior (control technique). In fact it is the quantification of these relationships which ultimately can lead to quantification of fidelity requirements.

Any particular transfer function can be considered in terms of at least four characteristics. We shall continue to address the particular four which were mentioned in connection with our definition of fidelity.

Threshold. Beginning with the aspect of threshold we would propose that a state is not usable if the pilot cannot detect a change in that state. Cab motion which is less than the vestibular system thresholds is

TABLE 3  
SIMULATOR-FIDELITY-RELATED STATES

MODALITY	CORRESPONDING STATES
<p>VESTIBULAR PERCEPTION</p> <p>(of motion taken with respect to an inertial reference frame)</p>	<ul style="list-style-type: none"> <li>• ROTATIONAL VELOCITIES <ul style="list-style-type: none"> <li>— three components</li> </ul> </li> <li>• SPECIFIC FORCES (translational acceleration) <ul style="list-style-type: none"> <li>— three components</li> </ul> </li> </ul> <p>(sensed states are subject to threshold, washout, and lag)</p>
<p>VISUAL PERCEPTION</p> <p>(of position or motion taken with respect to an earth fixed reference frame or with respect to another aircraft.)</p>	<ul style="list-style-type: none"> <li>• ROTATIONAL POSITION <ul style="list-style-type: none"> <li>— roll and pitch attitudes plus heading</li> </ul> </li> <li>• ROTATIONAL RATES <ul style="list-style-type: none"> <li>— rates of change of above aircraft states</li> </ul> </li> <li>• TRANSLATIONAL POSITION <ul style="list-style-type: none"> <li>— horizontal and vertical transverse positions plus range</li> </ul> </li> <li>• TRANSLATIONAL RATES <ul style="list-style-type: none"> <li>— horizontal and vertical transverse rates plus range rate</li> </ul> </li> </ul> <p>(The visually perceived states are also subject to threshold, lag, and washout but in different amounts from the vestibular states)</p>

useless, and visual motion less than the visual system resolution or the pilot's visual acuity is likewise useless. It may be necessary to either enhance the system (e.g., by adequate motion travel or increased visual system resolution) or enhance the pilot's perceptual power (e.g., by providing a g-seat or corrective lenses).

Analytical tools for dealing with thresholds are described in Graham and McRuer<sup>33</sup> and are compatible with the frequency domain methods commonly used with other pilot-vehicle elements.

Quickness. Quickness of response in either the motion or visual system has a direct impact on how tightly the pilot can regulate any of the states connected with a particular task. For example, if there is a large delay in the change of pitch attitude as presented to the pilot, then it is necessary for the pilot to make slower, more moderate pitch attitude control adjustments. Otherwise there is the likelihood of overcontrolling to the point of producing divergent pilot-induced oscillation in pitch attitude.

There is, of course, a basic limit on quickness of required simulator response which is set by the dynamics of the aircraft being simulated. The quickness of response inherent in the aircraft also sets a fundamental upper bound on the tightness of regulation which can be achieved by the pilot. Depending slightly upon the handling qualities of the aircraft, the following levels of quickness in terms of closed loop bandwidth are common<sup>34</sup>:

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33 Graham, Dunstan, and Duane McRuer, Analysis of Nonlinear Control Systems, McGraw Hill, New York, 1961.

34 Ringland, R. F., R. L. Stapleford, and R. E. Magdaleno, Motion Effects on an IFR Hover Task - Analytical Predictions and Experimental Results, NASA CR-1933, November 1971.

- Pitch and Roll Attitudes 1 rad/sec
- Vertical Flight Path 0.2 rad/sec
- Lateral Flight Path and Airspeed 0.1 rad/sec

The higher the desired bandwidth, the more critical the impact of additional motion or visual system delays. Hence, of the groups listed above, attitude control would be expected to be more susceptible to a lack of quickness in the simulator. Lateral flight path and airspeed would be less critical.

The sources of lags and delays in simulator systems are numerous and, to a degree, generally additive in their net effect. The effects of various sources of delay within real-time digital computing systems for flight simulators have been examined analytically by Heffley, et al.,<sup>35</sup> The objective of the examination was to explore useful simulation fidelity metrics and procedures for obtaining them. Emphasis is placed therein on digital computing systems involving two computers operating in series or within feedback loops in which there may be several forms of delays along with the complications arising from multirate or multiloop operation. Particular examples of delay discussed by Heffley, et al.,<sup>36</sup> include the following:

- Transport delay
- Data skewness (in time)
- Algorithmic delay

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<sup>35</sup> Heffley, Robert K., Wayne F. Jewell, Richard R. Whitbeck, and Ted M. Schulman, The Analysis of Delays in Simulator Digital Computing Systems. Volume One: Formulation of an Analysis Approach Using a Central Example Simulator Model, NASA CR-152340, February 1980.

<sup>36</sup> Ibid.

- Frame slip (two or more digital processors operating at nearly the same frame rates)
- Data exchange between two or more digital processors
- Multiloop or multirate architecture.

Visual flight simulator digital computing systems usually employ a "host" processor to represent the mathematical model of the aircraft and a "satellite" processor to generate the dynamic external visual field seen by the pilot in response to aircraft motions. Such an arrangement corresponds exactly to that of two digital computers operating in series within feedback loops wherein the human pilot also participates as a series element. Thus all of the delay phenomena described by Heffley, et al.,<sup>37</sup> as well as the multirate aspects handled by Whitbeck, et al.<sup>38</sup> are potential candidates for degrading the fidelity of the visual flight simulation employing digital computer-generated models of both aircraft and external visual field.

There is evidence that differences in the relative quickness of visual and motion modalities play a role in inducing effective pilot time delay — an important feature in the psychomotor behavior of the pilot.

"When other [than visual] modalities are available, such as rotary motion cues from a moving base simulator or actual aircraft, certain of the visual workload requirements can be reduced. In the case of rotary motions greater than semicircular canal threshold levels, the low-frequency lead generation requirements are reduced<sup>39</sup>. In essence, the rotary motion cues permit the pilot to close an inner loop akin to that of a rate

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37 Ibid.

38 Whitbeck, Richard F. and Dennis G.J. Didalensky, Multi-rate Digital Control Systems with Simulation Applications, AFWAL-TR-80-3101, Vol. 1, Sept. 1980.

39 Stapleford, Robert L., Richard A. Peters, and Fred R. Alex, Experiments and a Model for Pilot Dynamics with Visual and Motion Inputs, NASA CR-1325, May 1969.

gyro. The net effect is to reduce the effective whole-task time delay by about 0.15 sec (which also happens to be the time delay increment required to develop a first-order low-frequency lead)."<sup>40</sup>

Figure 6 (borrowed from Sinacori<sup>41</sup>) shows the effective pilot time delay versus motion drive bandwidth. Note that lack of motion response can contribute as much as a 2:1 effect in determining effective pilot delay. Baron et al.<sup>42</sup> also addresses this aspect of simulator fidelity.

Deficiencies in simulator response can sometimes be offset by trading off lags in the basic vehicle (aircraft model) with lags associated with the simulator motion or visual systems. For example, a lag in the motion drives could be offset, to some degree, by quickening the aircraft model response in either the control system or aerodynamic equations of motion. Similar fixes can be applied to the visual system. In general, all features — even nonlinear ones, can be expressed in useful terms in the frequency domain. Instead of rise time we would refer to bandwidth, or instead of washout time constant we would refer to washout frequency. Furthermore, pilot control strategy can be concisely stated in frequency domain terms. The manual control principles<sup>43</sup> are given in the frequency domain.

Summative statistical analysis permits additional freedom to express performance in terms of probability of occurrence or exceedence. But there are dangers in relying too heavily upon statistical measures for

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<sup>40</sup> Clement, W. F., D. T. McRuer, and R. H. Klein, "Systematic Manual Control Display Design," Guidance and Control Displays, AGARD CP-96, February 1972.

<sup>41</sup> Sinacori, J. B., The Determination of Some Requirements for a Helicopter Flight Research Simulation Facility, Systems Technology, Inc., Technical Report No. 1097-1, September 1977.

<sup>42</sup> Baron, Sheldon, Roy Lancraft, and Greg Zacharias, Pilot/Vehicle Model Analysis of Visual and Motion Cue Requirements in Flight Simulation, NASA CR-3312, October 1980.

<sup>43</sup> McRuer and Krendel, 1974, op cit.

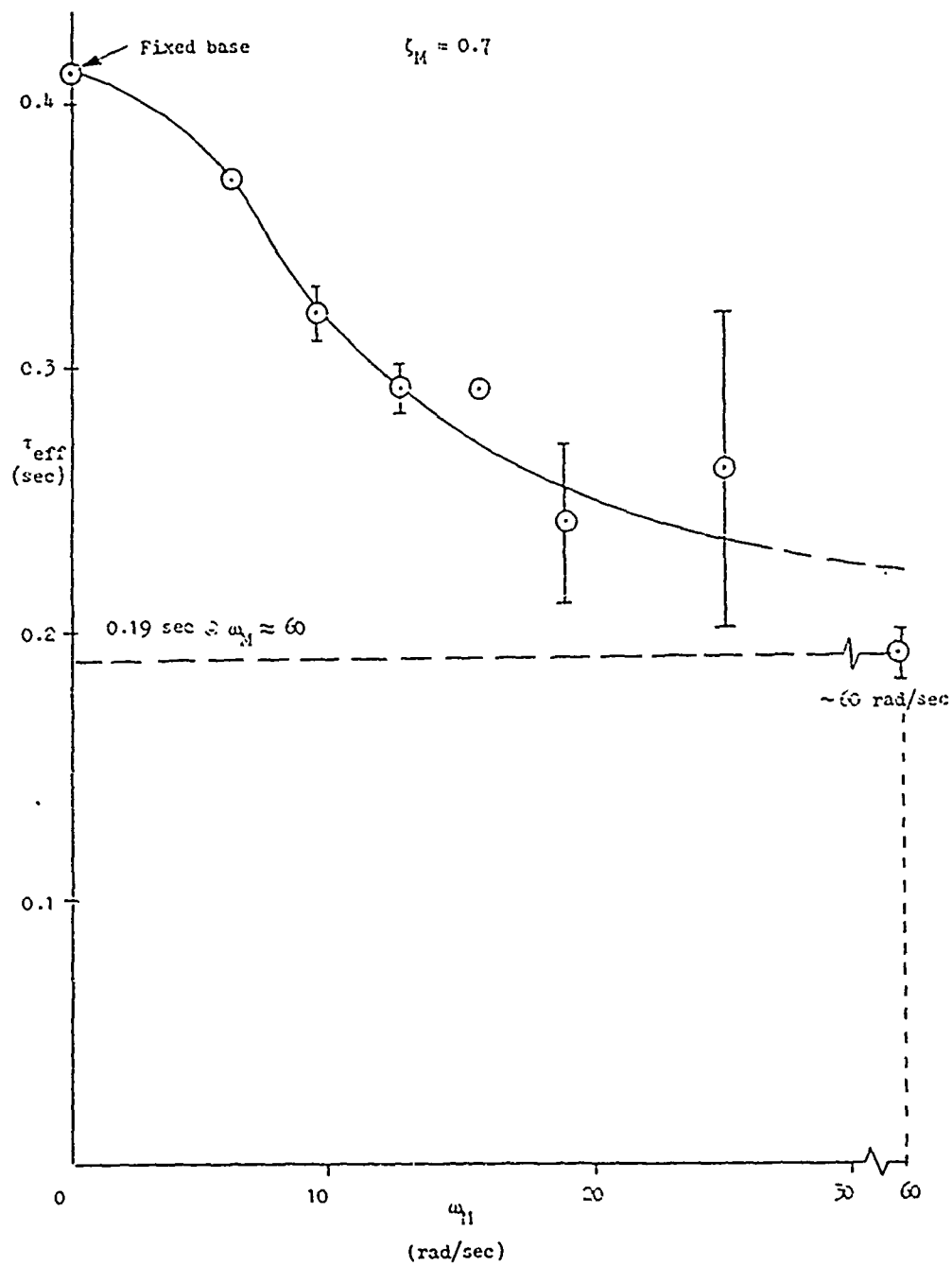


Figure 6. Effective Pilot Time Delay ( $\tau_{eff}$ ) Versus Motion Drive Natural Frequency ( $\omega_M$ )<sup>44</sup>

<sup>44</sup> Sinacori, 1977, op cit.



simulator fidelity. As was pointed out earlier, simulator performance can compare well with actual aircraft performance although the pilot may be using differing control techniques or may have differing perceptions. A better application of statistical analysis is perhaps in characterizing how individual pilot technique, or pilot perception parameters (time or frequency domain), are distributed for various subjects, levels of skill, or over the period of a given task. Statistical parameters have a great potential if applied to piloting technique as well as the usual measures of system performance.

Distortion. The distortion of states as perceived by the pilot can be responsible for inducing an incorrect application of control technique. Consequently, the distortion characteristic is a critical element in simulator fidelity.

Perhaps the most prevalent example of distortion is the level of motion washout necessary for working within a restricted motion travel. Due to washouts, sustained motion (angular rates or specific forces) is subject to gross distortion. As a result it is also necessary to scale down motion commands and to use gravity forces via pitch and roll angles to simulate long term specific forces. Sinacori<sup>45</sup> addresses motion distortion in a systematic way which includes presentation of supporting experimental results. We shall shortly discuss further experimental results which serve to define the respective roles of motion and visual modalities.

Visual distortion aspects appear to be far more subtle than for motion. It is fair to say that the simulator system characteristics which contribute to visual state distortion are not well understood at this time. It is possible, however, to infer the amount of distortion by observing pilot behavior, and an example involving range perception will be

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<sup>45</sup> Sinacori, The Determination of Some Requirements for a Helicopter Flight Research Simulation Facility, 1977, op cit.

presented in a later section. The work of Roscoe, et al,<sup>46</sup> concerning visual accommodation effects on apparent size and height should be considered with regard to the issue of distortion.

Signal-to-Noise Ratio. State noise is distinct from state distortion on the basis of randomness or lack of signal coherence. Noise can be generated by the pilot (this is often called remnant) or can result from system disturbances and uncertainties. This contributes to pilot workload by obscuring information content. This is more of a concern in the visual modality.

A summary of simulator-fidelity-related characteristics is given in Table 4.

#### **Domains**

The characteristics discussed previously can be expressed in a variety of ways but, generally speaking, will fall into one of the following:

- Time domain
- Frequency domain

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<sup>46</sup> Roscoe, Stanley N., "When Day is Done and Shadows Fall, We Miss the Airport Most of All," Proceedings of the 11th NTEC/Industry Conference, NAVTREQUIPCEN IH-306, Naval Training Equipment Center, Orlando, Florida, November 14-16, 1978.

Roscoe, Stanley N., Ground-Referenced Visual Orientation with Imaging Displays: Final Report, AFCSR-79-4, November 1979.

Randle, Robert J., Stanley N. Roscoe, and John C. Petitt, Effects of Magnification and Visual Accommodation on Aimpoint Estimation in Simulated Landings with Real and Virtual Image Displays, NASA TP 1635, October 1980.

TABLE 4  
STATE TRANSFER RELATIONSHIP CHARACTERISTICS  
MOTION-VISUAL ANALOGIES

CHARACTERISTICS	VESTIBULAR	VISUAL
Threshold	Vestibular thresholds	Static resolution, dynamic resolution, line width
Quickness (lag, delay, initial response bandwidth)	Motion bandwidth effective throughput, delay, effective lag	Visual update, effective lag
Distortion (shape of response, correlation among multiple stimuli) — implies sufficient amplitude	Flatness of frequency response, washout time constant  — Motion travel, velocity, acceleration	Perceived range, size, height factors  — Field of view, depth of field, maximum brightness, contrast
Signal-to-Noise (cleanliness)	Vibration, rumble	Acuity, detail, contrast, jitter, flicker

Each of the above domains offers potential benefits in terms of convenience of measurement, availability of data, and compatibility of description between the human operator and the simulator system.

The time domain is usually the least abstract and it is possible to easily handle such features as thresholds, response, or decay times. Furthermore pilot control technique or control strategy can be easily cast in terms of time domain differential equations or finite difference equations<sup>47</sup>. Working strictly in the time domain becomes a disadvantage when we attempt to work with the overall pilot-vehicle system.

The frequency domain, on the other hand, enables us to use powerful analytic tools while combining the various elements in a simulator or actual aircraft system.

#### **Fidelity Versus Training Effectiveness**

The value of a training simulator is typically measured in terms of its ability to reduce total cost-to-train. Its ability to reduce training costs is, in turn, a function of (a) its training effectiveness, and (b) the relative cost of simulator and aircraft training. Training effectiveness or "transfer of training" has most often been measured in terms of (a) transfer percent, i.e., the percent of time normally required in the aircraft which can be eliminated as a result of simulator training; and/or (b) the cumulative transfer effectiveness ratio (CTER) defined by Roscoe<sup>48</sup> as the ratio of time saved in the aircraft to time spent in the

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47 Heffley, Robert K., and Wayne F. Jewell, Development of a CTOL Piloting Technique Measurement Scheme for a Real-Time Simulator Environment, NASA CR-152294, July 1979.

48 Roscoe, S. N., "Incremental Transfer Effectiveness," Human Factors, 13, 1971, pp. 561-567.

simulator. Carter<sup>49</sup> illustrated the hypothetical relationships between these parameters and stressed the importance of including both parameters in pilot training system cost-effectiveness models, noting that transfer percent is a measure of training effectiveness while CTER is a measure of training efficiency. More recently, Bickley<sup>50</sup> has shown that both of these parameters and the interaction between them can be modeled by means of a single differential equation, an approach which facilitates the calculation of the most cost-effective mix of simulator and aircraft training.

An implicit assumption in the present approach to determining fidelity requirements is that the training effectiveness of a given simulator will be highly correlated with the ability of the simulator to induce pilot behavior which is similar to that exhibited in the aircraft; i.e., the higher the similarity between simulator and aircraft behavior the greater the potential for high transfer of training. Regardless of how fidelity is defined, simulator fidelity is a necessary, but not a sufficient, condition for training effectiveness. This is due to the significant impact on transfer of such factors as the instructional features incorporated in the device and the way in which the device is used. Thus the present approach, after developing a sufficiently accurate model of pilot behavior in the aircraft, will enable the analyst to predict whether the fidelity of a given simulator is sufficient to at least permit a high degree of transfer. It is not possible, however, to predict the actual aircraft hours which can be replaced or time required in the simulator without accurately modeling the effects of such factors as the non-fidelity-related design features and method of utilization. It should be noted, however, that the ability to make accurate statements about whether a

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49 Carter, V. E., "Training Effectiveness Analysis," Appendix XV, Future Undergraduate Pilot Training System Study: Final Report, Aeronautical Systems Division, Air Force Systems Command, WPAFB, Ohio, March 1971.

50 Bickley, William R., "Optimizing Simulator-Aircraft Training Mixes," Proceedings of the 2nd Interservice/Industry Training Equipment Conference, November 1980.

given simulator will provide the essential cues required to permit a high degree of transfer is, in itself, a worthwhile objective.

#### IMPLICATIONS FOR DETERMINING FIDELITY REQUIREMENTS

The approach to simulator fidelity described above establishes a point of departure for the remaining sections. At the same time we will refine and expand the ideas presented here.

The single most important notion in our discussions of simulator fidelity is that fidelity, or the lack thereof, is most directly tied to

- Pilot perception of states involved in a particular task, and
- Pilot behavior in terms of control actions in carrying out the task.

A less direct measure of fidelity is the simulator response (motion or visual), per se. Fidelity of simulator response is seen not with reference to mimicking the "real world" but with reference to inducing pilot perception and control technique. Nevertheless, simulator response or performance must ultimately be addressed when expressing simulator construction standards. Hence parameters which indicate fidelity of perception or behavior must, in turn, be converted to system performance needs. This step will be considered in later sections.

Another major implication of the above approach to simulator fidelity is that pilot behavior in terms of specific task loop structure needs to be quantifiable and measurable. Both are realizable. The means of quantification has been extensively developed. Measurement of pilot behavior is less perfected, but there are a number of methods to measure pilot actions, and these methods are continually being improved. One area where measurements need to be more fully exploited, however, is in quantifying

and cataloging pilot behavior in full task situations rather than in performing partial tasks. Furthermore, the process of making such measurements — both in flight and in simulators — will itself expose and illuminate concepts of simulator fidelity. Specific suggestions for measurements will be the objective of a later section.

Our next step, however, is to consider how to quantify the context in which simulator fidelity must be considered — the training missions themselves. Hence Army training missions and their translation into closed pilot-vehicle loop structure will be considered in the next section.

## **ANALYSIS OF ARMY FLIGHT TRAINING MISSIONS**

The value of understanding the training mission and piloting task was emphasized in the earlier section. The goal now is to develop further that understanding in specific terms which are useful for the ultimate objective — prescribing levels of simulator fidelity needed to train.

We shall begin this section with a definition of the training missions to be considered and follow it with a description of how to formulate analytical descriptions of flight tasks and associated piloting technique. The latter is based on manual control theory and a recognition of how pilots nominally operate aircraft based on written training material as well as discussions with pilots regarding piloting technique for specific tasks. A secondary concern is to link control strategies with the vehicle dynamics, information available to the pilot, control characteristics, and external disturbances. Beyond this we also want to consider skill development in terms of compensatory, pursuit, and precognitive behavior (i.e., the successive organization of perception or SOP).

### **ARMY TRAINING OBJECTIVES TO BE CONSIDERED**

The procedure for accomplishing the above begins with a review of the various Army training missions and piloting tasks to be considered. This will be followed by a discussion of guidelines for determining and describing task loop structure. Finally we shall consider a number of specific task analyses which pertain to Army flight training missions. All of this will be preparatory to the subsequent section dealing with analytic tools for describing motion and visual fidelity.

The scope of this study covers a wide spectrum of Army training missions including both rotary- and fixed-wing aircraft with the level of training spanning undergraduate through continuation training. Of



particular interest are the critical flight phases which include nap-of-the-earth navigation, weapons delivery, terrain following, and low-level maneuvering. Operating environments to be considered include both visual meteorological conditions (VMC) and instrument meteorological conditions (IMC). The aspect of our approach which makes consideration of such a wide spectrum of conditions feasible is that there is the ability to divide these training missions into basic components and to find areas of commonality for simulator fidelity requirements.

A basic list of Army flight training objectives (i.e., fundamental flight tasks) was compiled based upon a review of the Aircrew Training Manuals (ATMs) for the various Army aircraft types such as utility fixed wing, utility helicopter, cargo helicopter, etc<sup>51</sup>. Table 5 shows this list without specific regard to aircraft type. The table is a grouping of individual piloting tasks considered to be basic training components according to the ATMs. The list was also crosschecked against the helicopter field manual<sup>52</sup>, the basic undergraduate training syllabus for

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<sup>51</sup> Anon., Aircrew Training Manual. Utility Helicopter, Department of the Army, TC 1-135, October 1978.

Anon., Aircrew Training Manual. Attack Helicopter, Department of the Army, TC 1-136, October 1978.

Anon., Aircrew Training Manual. Observation Helicopter, Department of the Army, TC 1-137, October 1978.

Anon., Aircrew Training Manual. Cargo Helicopter, Department of the Army, TC 1-139, October 1980.

Anon., Aircrew Training Manual. Surveillance Aircraft, Department of the Army, TC 1-144, October 1978.

Anon., Aircrew Training Manual. Utility Aircraft, Department of the Army, TC 1-145, October 1980.

<sup>52</sup> Anon., Rotary Wing Flight, U. S. Army Field Manual No. 1-51, 16 April 1979.

TABLE 5

ARMY FLIGHT TRAINING OBJECTIVES<sup>53</sup>BASIC FLIGHT

- Straight and Level
- Climb/Descent
- Level Turns
- Climb/Descending Turns
- Acceleration/Deceleration
- Traffic Pattern
- Slow Flight
- Stalls

HOVERING

- Takeoff to Hover
- Hover
- Hover Checks
- Hover Turns
- Forward Hover
- Land from Hover
- Hover Out of Ground Effect
- Confined Area
- Pinnacle/Ridgeline
- Slope

TAKEOFF

- Normal Takeoff
- Maximum Performance
- Short Field
- Obstacle Clearance
- Terrain Flight Takeoff

APPROACH/LANDING

- Normal Approach/Landing
- Steep Approach
- Shallow Approach
- Go Around
- Short Field
- Obstacle Clearance
- Terrain Flight Approach
- VASI Approach

LOW ALTITUDE OPERATIONS

- Terrain Flight Navigation
- Low Level Flight
- Contour Flight

LOW ALTITUDE OPERATIONS (CONCLUDED)

- NOE Flight
- Unmask/Remask
- Quickstop
- Evasive Maneuvers

WEAPON DELIVERY

- Hover Fire
- Running Fire
- ACM

INSTRUMENT FLIGHT

- Takeoff
- Level Flight
- Turns
- Timed Turns
- Climbs/Descents
- Climb/Descending Turns
- Acceleration/Deceleration
- Autorotation
- VOR Navigation
- ADF Navigation
- Holding
- Unusual Attitude Recovery
- Navaid Approach
- GCA Approach
- Tactical Instrument Takeoff
- Tactical Instrument Approach

EMERGENCIES

- Hover Autorotation
- Standard Autorotation
- Standard Autorotation With Turn
- Low-Level Autorotation
- Hydraulic Malfunction
- Anti-Torque Malfunction
- Engine Failure at Altitude
- Engine Failure at Hover
- Flight at  $V_{MC}$  (Single Engine)
- Single Engine Landing
- Single Engine Go Around
- Engine Failure at Takeoff
- Engine Failure During Approach

<sup>53</sup> Bullets indicate those tasks which are at least partially quantified.

Army rotary-wing pilots<sup>54</sup> and, for more specialized tasks, the helicopter gunnery manuals<sup>55</sup> and the NOE task analyses of Gainer and Sullivan<sup>56</sup>.

The major groupings for Table 5 imply either a common piloting loop structure (as in cases of basic flight or hovering tasks), a class of maneuvers (such as takeoff and approach and landing), a basic environment (low altitude operations or weapon delivery), or a basic limitation on modality of pilot information (as in instrument flight tasks). This classification system is not a rigid, well-defined form; but it is a complete and convenient checklist of flight training objectives to be considered in our analyses.

Another list which is convenient to consider at this stage is a control technique taxonomy for fixed- and rotary-wing aircraft as given in Table 6. This shows a list of control techniques which are more or less independent of the piloting tasks which they support. For example control techniques for pitch and roll control are common to nearly every piloting task or training objective regardless of the aircraft type, the environmental condition, or the level of training. Likewise heading, speed, and flight path control are common to most tasks. Note that the control techniques are grouped first according to their place in the overall loop structure, i.e., whether they are inner loops, intermediate loops, or outer loops; second, the aircraft axis; and finally, whether they are related to a basic compensatory level or pursuit level of operation (the distinction will be discussed further in this section). One of our objectives will be to quantify control technique using existing data from direct pilot technique measurements and, further, to generalize these data to as many of the piloting tasks, shown in Table 5, as is possible.

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<sup>54</sup> Anon., Program of Instruction for 2C-15A/2C-100B-B, Officer/WO Rotary Wing Aviator Course, U. S. Army Aviation Center, Ft. Rucker, Alabama, SSI/MOS: 15A/100B, February 1978.

<sup>55</sup> Anon., Helicopter Gunnery, Department of the Army, TC 1-4, September 1976.

<sup>56</sup> Gainer and Sullivan, 1976, op cit.

TABLE 6

CONTROL TECHNIQUE TAXONOMY FOR FIXED-WING AND ROTARY-WING AIRCRAFT

Compensatory Level Techniques

I. ATTITUDES (Inner loops)

A. Pitch (perceived horizon, artificial horizon, pitch director, "right-side-up," etc.)

1. Normal: Pitch + Stick

B. Roll (perceived horizon, artificial horizon, roll director, "right-side-up," etc.)

1. Normal: Roll + Lateral Stick

2. "Rudder to Bank": Roll + Pedal (applicable at high AOA)

C. Yaw (runway line-up, compass, D G , etc.)

1. Normal: Yaw + Pedal (short final approach, hover)

II. FLIGHT PATH (Intermediate loops)

A. Vertical (altitude, sink rate, flight path angle, ILS glide slope, VASI, etc.)

1. "Frontside": Flight Path + Pitch Command (applicable for  $V > V_x$ )

2. "Backside": Flight Path + Throttle (applicable for  $V < V_x$ )

3. "Forward Slip": Flight Path + Slip (to steepen approach path)

B. Lateral (heading, turn rate, drift, VOR, localizer, etc.)

1. "Bank-to-turn": Turn Rate + Roll Command (usually coordinated)

2. "Bank-to-Translate": Drift + Roll command (slip)

3. "Yaw to Turn or Translate": Drift + Yaw Command (skid)

C. Fore and Aft (applicable only to hovering vehicles)

1. Normal: Surge + Pitch Command (deceleration, hover)

2. "Direct x-Force": Surge + x-Force (e.g., where nozzle deflection variable)

TABLE 6 (Continued)

III. FLIGHT CONDITION (Outer loop or trim)

A. Speed (airspeed, groundspeed, angle of attack, stall horn, etc.)

1. "Frontside": Speed + Throttle (applicable for  $V > V_x$ )
2. "Backside": Speed + Pitch Command (applicable for  $V < V_x$ )

B. Engine State (rpm, manifold pressure, EPR, etc.)

1. Throttle: Thrust + Throttle
2. Governor: Thrust + RPM Command (can be a configuration state also)

C. Symmetry (lateral acceleration, ball, sideslip, etc.)

1. Normal: Lateral g + Pedal (for coordination or trim)
2. "Wing-Low": Lateral g + Roll Command (for x-wind, engine-out, etc.)

IV. CONFIGURATION (Open loop or very loose loop)

A. High Drag (flaps, gear, speed brake, etc.)

1. "Flight Condition Adjustment": Speed + Flaps, Gear, Speed Brake
2. "Flight Phase Appropriate": Checklist + Flaps, Gear

B. Augmentation (SAS, SCAS, autopilot, flight director)

1. Workload Relief: Off + On
2. "Normal Operation": On (normal operating mode, safety of flight, etc.)

C. Failure (engine, airframe, systems, etc.)

1. "Direct Action"
2. "Ignore" (not important, unaware, etc.)

TABLE 6 (Concluded)

**Pursuit Level Techniques**  
(Feedforward loop structure involving controls,  
states, errors, and disturbances)

**I. ATTITUDES**

**A. Pitch**

1. "Avoid Extremes": Pitch  $\rightarrow$  Stick (stall avoidance,  $V_{NE}$  avoidance, etc.)

**B. Roll**

1. "Avoid Extremes": Roll  $\rightarrow$  Lateral Stick

**C. Yaw**

1. "Collective-to-Pedal": (counter yaw)

**II. FLIGHT PATH**

**A. Vertical**

1. "Flare" Height  $\rightarrow$  Attitude (or collective)
2. "Flaps-to-Pitch" crossfeed (to counter height excursion)
3. "Flaps-to-Throttle" (to counter height excursion)

**B. Lateral**

1. "Coordinated Turn": Bank  $\rightarrow$  Pedal
2. "Cross-Control": Bank  $\rightarrow$  Pedal (to correct x-wind drift)

**III. FLIGHT CONDITION**

**A. Speed**

1. "Pitch-to-Throttle" Crossfeed (frontside operation - to counter speed change)
2. "Throttle-to-Pitch" Crossfeed (backside operation)
3. "Flaps-to-Pitch" Crossfeed
4. "Flaps-to-Throttle" Crossfeed (to counter speed excursion)
5. "Chop the Throttle" (short final approach)

**B. Engine State**

1. Collective-to-Throttle (to counter rpm change)

**C. Symmetry**

1. "Throttle-to-Pedal" Crossfeed (counter propeller asymmetry)

A review of the existing manual control literature reveals that a quantification in terms of piloting tasks and piloting technique is lacking. Where pilot technique has been directly measured in manual control theory terms, it has generally been associated with: (a) inner loop piloting tasks such as regulation of pitch and/or roll attitude, by means of their respective controls; (b) simultaneous roll attitude and yaw rate regulation by means of two controls<sup>57</sup>; (c) inner- and outer-loop regulation of height by means of a single control<sup>58</sup>; or (d) inner and outer loop regulation of speed and position by means of a single control<sup>59</sup>, all based on instrument flight techniques. A few measurements<sup>60</sup> have been taken for an overall piloting task in which inner loops, such as attitudes, are used in direct support of outer loops, such as position, altitude, and heading. Thus, even though the inner loop measurements which do exist are widely applicable to many of the training missions and piloting tasks listed in Table 6, we lack the important quantification of the outer loop behavior, especially in critical tasks such as nap-of-the-earth operation, approach and landing, or air-to-air combat; and these are areas where

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57 Stapleford, R. L., D. T. McRuer, and R. E. Magdaleno, Pilot Describing Function Measurements in a Multiloop Task, NASA CR-542, August 1966.

58 Weir, D. H., and D. T. McRuer, Pilot Dynamics for Instrument Approach Tasks: Full Panel Multiloop and Flight Director Operations, NASA CR-2019, May 1972.

Stapleford, R. L., S. J. Craig, and J. A. Tennant, Measurement of Pilot Describing Functions in Single-Controller Multiloop Tasks, NASA CR-1238, January 1969.

Heffley and Jewell, 1979, op cit.

Jewell, Wayne F., and Ted M. Schulman, A Pilot Control Strategy Identification Technique for Use in Multiloop Control Tasks, Systems Technology, Inc., Technical Report No. 1153-2, August 1980.

59 Clement, Warren F., R. Wade Allen, and Dunstan Graham, Pilot Experiments for a Theory of Integrated Display Format (Final Report), JANAIR Report No. 711107, October 1971.

60 Ringland, Stapleford, and Magdaleno, 1971, op cit.

definition of visual and motion simulator fidelity requirements is probably of most interest.

It will be the objective of the remainder of the section to develop the quantitative data which are available for piloting tasks and piloting technique to show where these data are applicable to Army flight training missions and to demonstrate ways of extending or extrapolating existing data to cover the various areas of interest to the Army.

#### **GUIDELINES FOR DESCRIBING TASK LOOP STRUCTURE**

Let us now consider a simple basic set of guidelines and rules for describing task loop structure for a given statement of the task and some understanding of the vehicle dynamics and operating environment. We shall gain from this a useful point of perspective for viewing the specific task analyses to be presented in the subsequent subsection and beyond that, to lead into the discussion of analytic tools for describing fidelity in the next section.

Simply stated, the primary rationale for describing task loop structure is first to define the overall piloting objective and, second, to discover how the piloting objective might be successfully executed working within (a) the constraints of the information available, (b) the aircraft dynamics, and (c) the workload limitations of the pilot. In general, to satisfy all of these constraints, the execution of a primary task objective requires the use of a multiloop structure for which there are nested intermediate loops (series loop structure) accompanied by a similar set of nested loops for each additional axis of control (parallel loop structure). Samples of this general structure are shown in Figs. 7 through 11. Figure 7 shows an acceleration/deceleration maneuver in a utility helicopter. The basis for this control structure is the task description



TASK: Perform Acceleration/Deceleration

CONDITIONS: In a VM or an STTS, during day, VMC, given an altitude, and minimum deceleration attempted.

STANDARDS:

- ① 1. Maintain stated entry and minimum deceleration altitudes  $\pm 10$  ft.
- ② 2. Maintain altitude  $\pm 100$  feet.
- ③ 3. Maintain heading  $\pm 5$  degrees.
- ④, ⑤ 4. Maintain aircraft in trim. (Integral Compensation)

DESCRIPTION: To initiate the maneuver, simultaneously reduce collective and apply aft cyclic to obtain the minimum deceleration attempted. ② Maintain entry altitude with collective and heading with cyclic. ④ Adjust pedals to maintain trim. As the aircraft approaches minimum deceleration attempted, simultaneously increase collective to maintain altitude and apply forward cyclic to accelerate to entry altitude. Adjust pedals to maintain trim. Attitude cross-check is made primarily by visually referencing the horizon and aircraft flight instruments. ①, ⑤

REFERENCES:

FM 1-5

FM 1-51

Operator's Manual

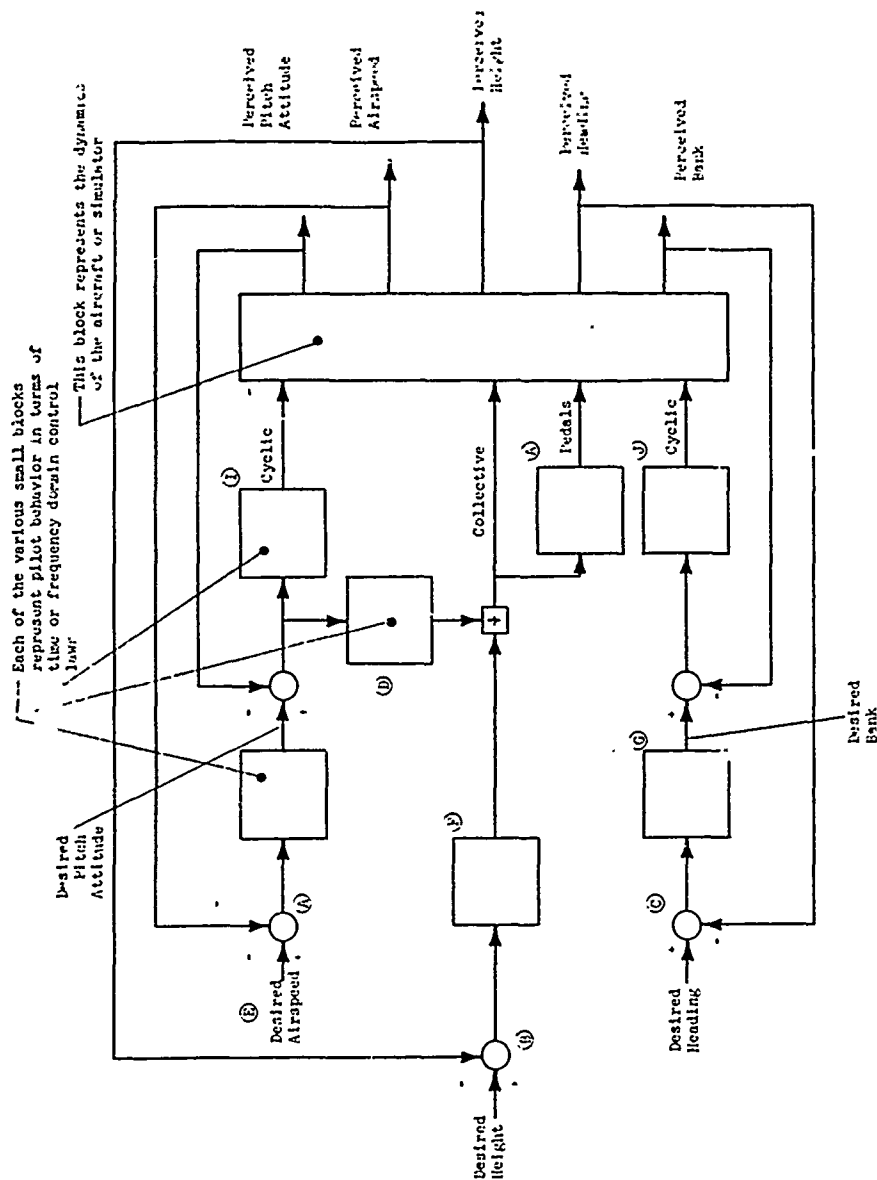
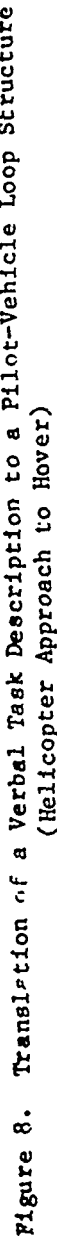


Figure 7. Pilot-Vehicle Diagram of Acceleration/Deceleration Maneuver — Utility Helicopter



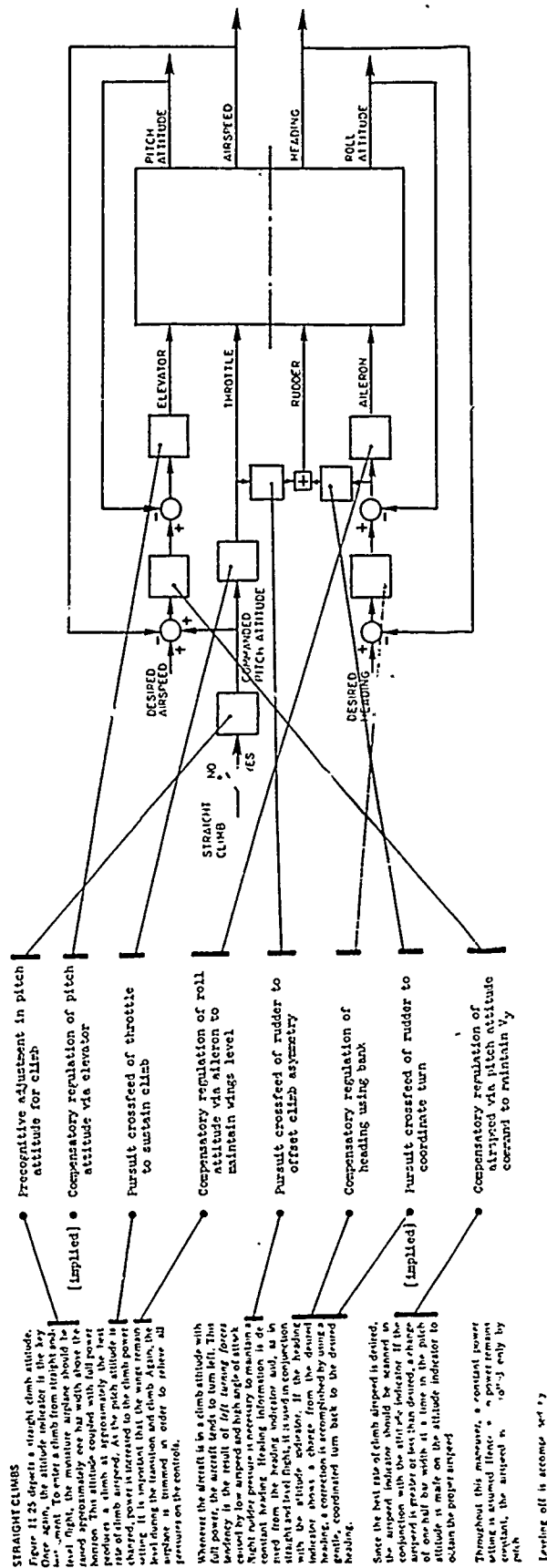


Figure 9. Translation of a Verbal Task Description to a Pilot-Vehicle Loop Structure (Straight Climb on Instruments)

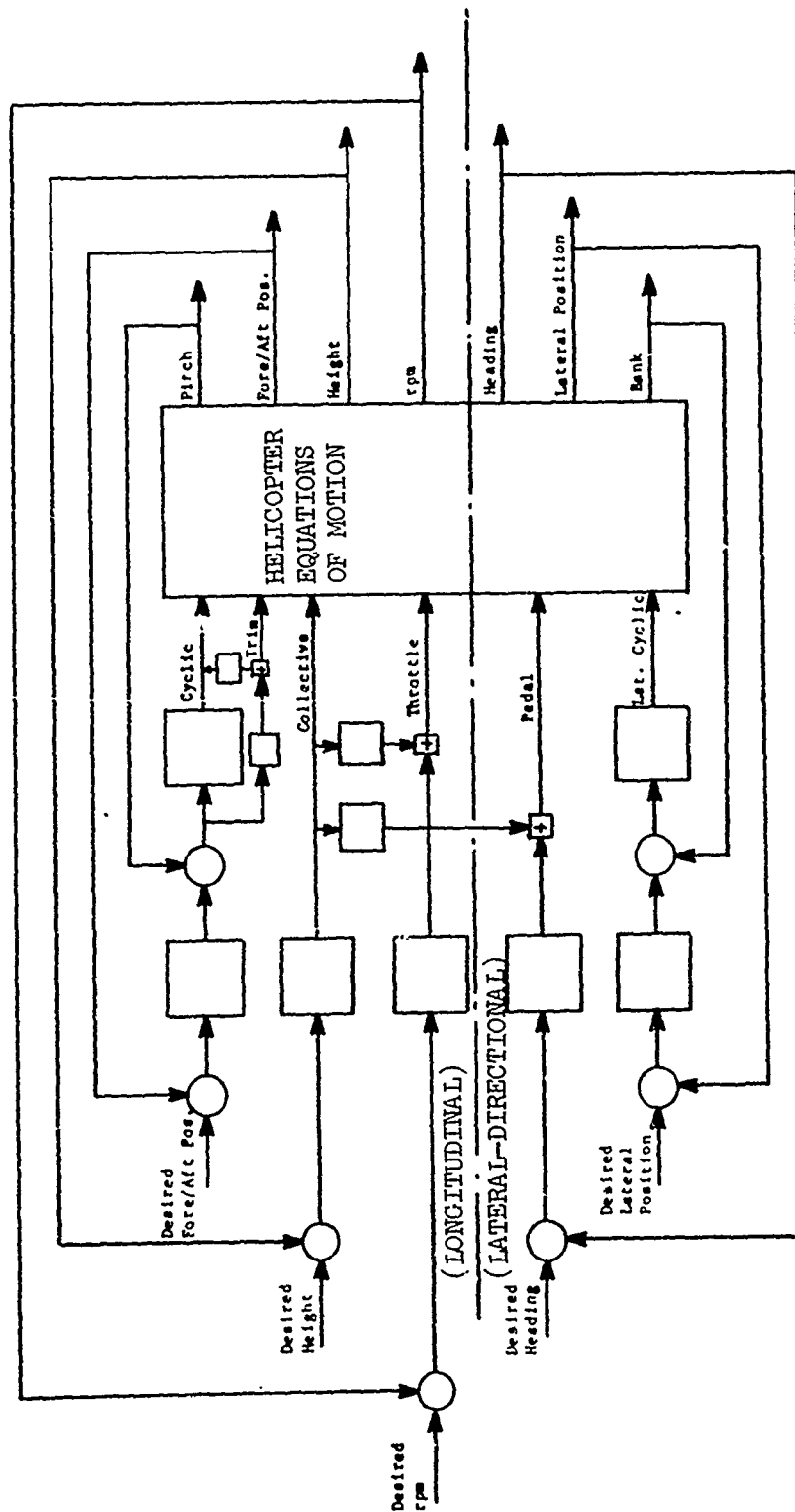


Figure 10. Common Loop Structure, Hovering Flight Tasks — Helicopter

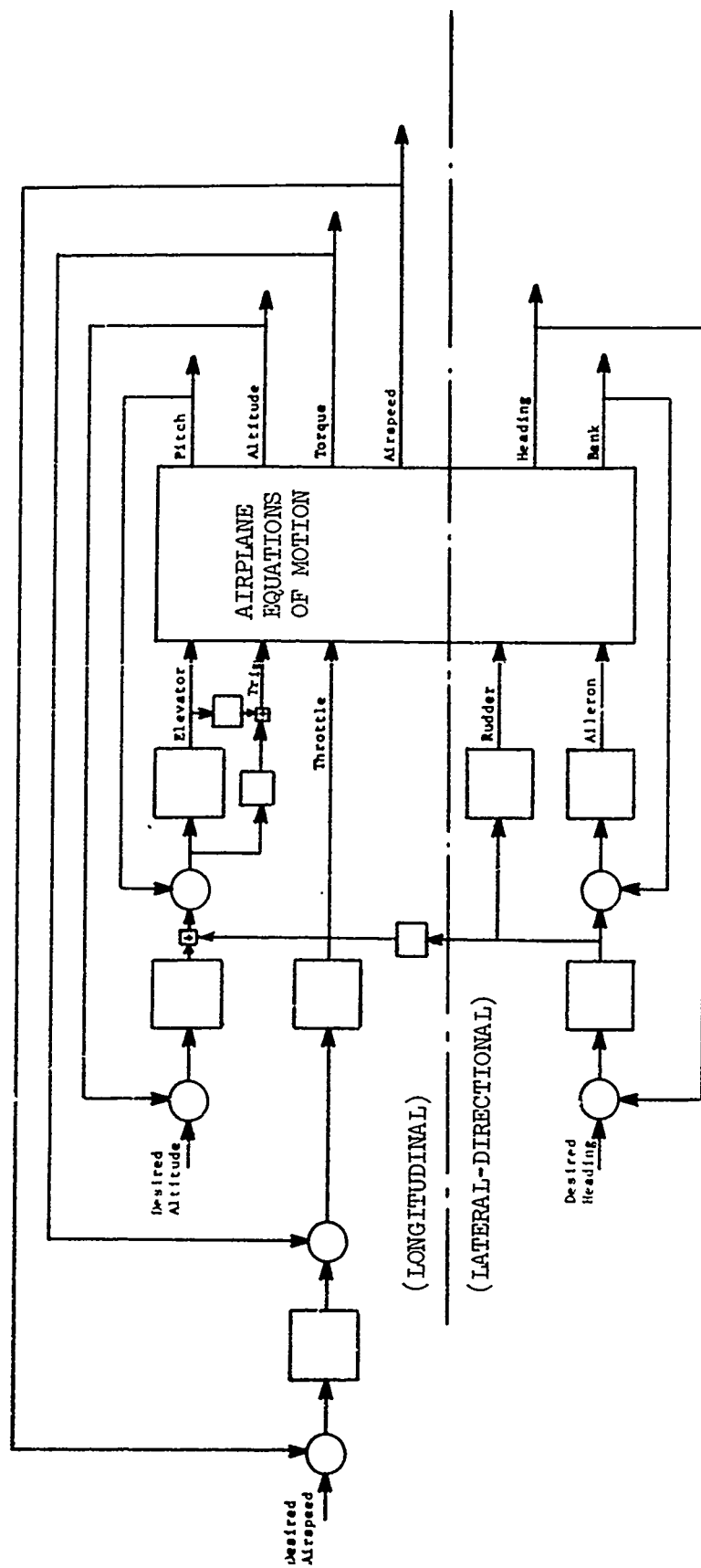


Figure 11. Common Loop Structure, Basic Flight Tasks — Fixed-Wing, Frontside Technique

provided for Army aviators in the aircrew training manual.<sup>64</sup> Figure 8 similarly describes the pilot-vehicle loop structure which can be inferred from a literal interpretation of another training manual task description.<sup>65</sup> In this case an approach to hover is considered. Note that the structure is similar to the previous case except that range perception is involved and manual control of rotor rpm is addressed. Figure 9 shows the inferred loop structure for a straight climb on instruments<sup>66</sup> which is equally applicable to both helicopters and fixed-wing aircraft. Additional examples of common loop structure are shown in Figs. 10 and 11 for helicopter hovering and fixed-wing frontside operation, respectively.

In each of the above examples only the general loop structure is described — there is no quantification of the various pilot or vehicle elements. Quantification is required, however, if these diagrams are to be used for determination of simulator fidelity requirements. Pilot-vehicle loop structure can be quantified by direct measurement of piloting technique and aircraft response; however, estimates can be made by direct literal interpretation of pilot training manual descriptions.<sup>67</sup> Some examples are shown below.

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<sup>64</sup> Anon., ATM, Utility Helicopter, 1978, op cit.

<sup>65</sup> Anon., Basic Helicopter Handbook, 1965, op cit.

<sup>66</sup> Anon., Jeppesen Commercial Instrument Manual, 1977, op cit.

<sup>67</sup> Heffley, Robert K., and Ted M. Schulman, Derivation of Human Pilot Control Laws Based on Literal Interpretation of Pilot Training Literature, AIAA Paper No. 81-1822, 1981.

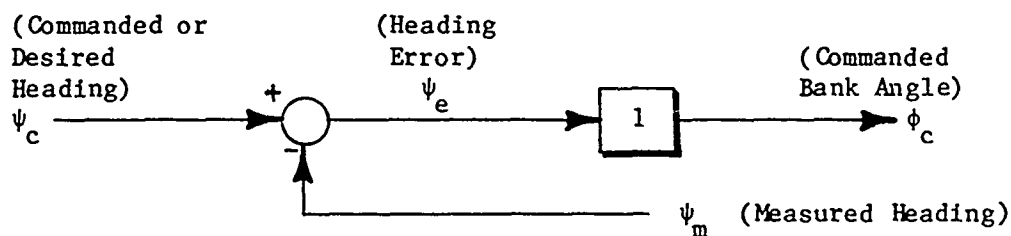
To illustrate the concept of flight task quantification, consider a simple example — heading regulation during cruising flight. The instructions for executing a small amplitude level turn are:

"As a guide for turns of 30 deg or less, the bank angle should approximate the number of degrees to be turned."<sup>68</sup>

This implies the following piloting technique relating bank angle command,  $\phi_c$ , to heading error,  $\psi_e$ :

$$\phi_c = \psi_e$$

Or, in block diagram form the piloting technique is:



Note that this piloting technique is not dependent upon vehicle dynamics or flight condition; it is invariant.

Combining the above piloting technique with the vehicle dynamics involved in turns (i.e., turn rate,  $\dot{\psi}$ , equals bank angle,  $\phi$ , times the kinematic ratio of gravity acceleration to airspeed,  $g/U$ ) we obtain the

<sup>68</sup> Anon., Instrument Flying, Air Force Manual, AFM 51-37, 15 August 1979.

simple pilot-vehicle feedback loop structure shown in Fig. 12. It should be noted that the numerical piloting technique indicated here could be inserted directly into the heading regulation blocks in several of the task loop structures shown previously (e.g., in Figs. 7, 8, 9, and 11). Also note that the basic form of the loop structure in Fig. 12 follows that of Fig. 5 in which basic fidelity components are identified.

Other techniques can also be applied to defining specific piloting tasks and training objectives. Besides direct measurement of piloting technique and interpretation of training literature, Carter<sup>69</sup> has found that considerable insight can be gained by asking instructor pilots not only how but how not to perform specific tasks or maneuvers (i.e., potential errors). In fact the latter appears to be substantially better in provoking a good task analysis than the former. While this procedure may not aid directly in numerical definition, it can be useful in refining or testing a basic task loop structure hypothesis.

Studying the errors in the performance of actual flight tasks can also be a useful technique in identifying cues used by the pilot. More specifically, errors frequently occurring in the simulator which never or rarely ever occur in the aircraft can lead to the identification of real world cues to correct performance that is missing or distorted in the simulator. For example, the tendency of students to always pull up late in a Northrop simulation of the F-4J barrel roll attack was traced to a probable target minification effect, apparently caused by the eye's tendency to return to a resting accommodation in the absence of textural detail, as described by Roscoe<sup>70</sup>. Conversely, the failure of a simulator

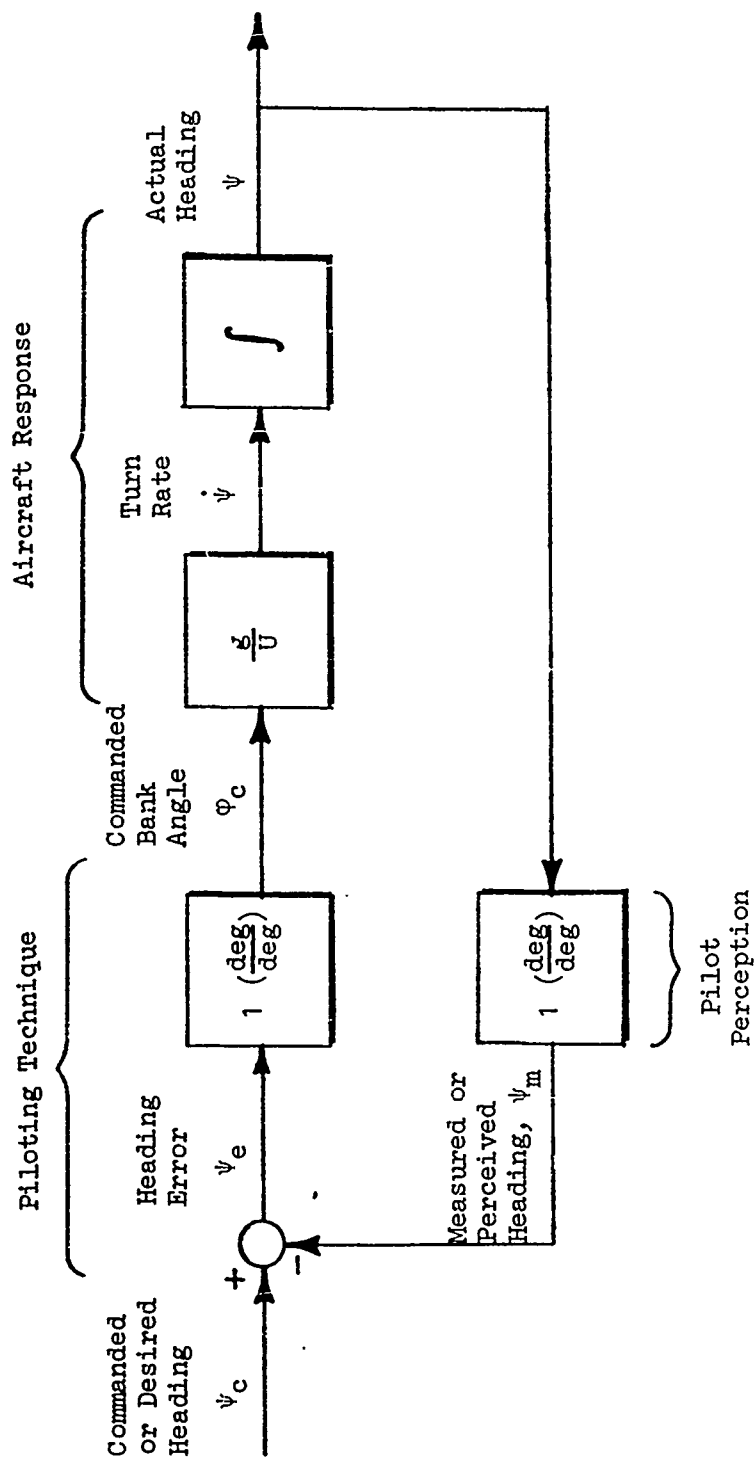
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69 Carter and Semple, 1976, op cit. It should be noted that this involved development of a task description for a complicated fixed-wing air combat maneuver — the "barrel roll attack."

70 Spring, W. G., "Simulation Development and Preparation," Volume 4 of Experiments to Evaluate Advanced Flight Simulation in Air Combat Pilot Training, NOR 76-52, Northrop Corporation, March 1976.

Roscoe, S. N., 1978, op cit.





Note: For flight at 100 kt,  $\frac{g}{U} = \frac{32 \text{ ft/sec}^2}{169 \text{ ft/sec}} = 0.2 \text{ sec}^{-1}$

Hence the closed-loop gain is 0.2 rad/sec — indicative of low to moderately-tight regulation

Figure 12. Simplified Heading Regulation Task Loop Structure with Quantification of Pilot-Vehicle Elements

to induce an error which normally occurs in the aircraft can help pinpoint artifactual cues which do not exist in the real world or to identify missing or inadequately simulated distracting cues and workload factors which make the task unrealistically easy in the simulator in order to correct performance.

Important clues to how piloting technique might be adjusted in terms of control gains or control compensation can be obtained from manual control theory. This subject will be discussed at length in the next section of the report.

It should be emphasized that all available sources should be utilized in the construction of quantitative models of training objectives in terms of flight tasks and piloting technique. No single source is likely to provide a complete picture.

#### **SPECIFIC TASK ANALYSES**

Few examples exist of even partially quantified pilot-vehicle loop structures for full-task analyses. A review of the literature shows an emphasis on loop structures for partial task analysis, and this is limited mainly to inner-loop aspects. The following Figures 13 through 22 depict some of those few cases where relatively complete outer loop tasks have been considered and, to some degree, quantified. Note that each task is described first verbally and then in terms of a feedback control block diagram. In each case an attempt is made to focus only on the primary task loop. In the interest of simplicity, supporting or secondary loops are omitted (e.g., for a speed change maneuver only the longitudinal control axis is addressed — supporting pitch attitude control and control of other axes are not shown explicitly.)

## Verbal Description

Adjust bank angle by applying appropriate pressure to the lateral cyclic stick. Monitor roll response using either the actual horizon or the cockpit artificial horizon.

## Feedback Control Description

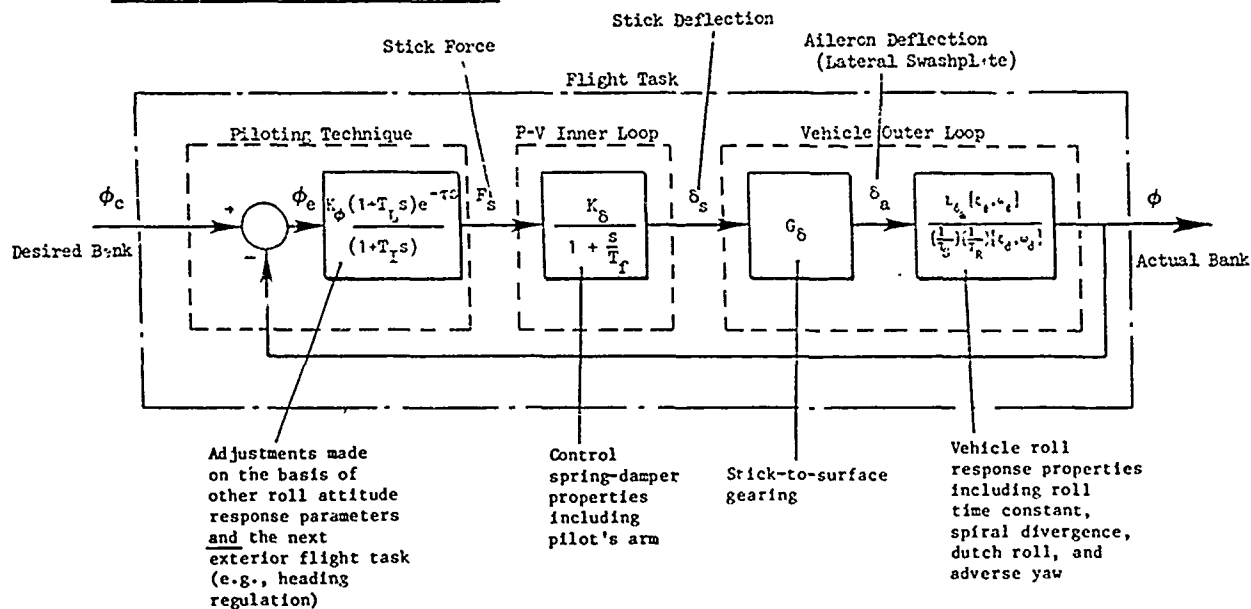


Figure 13. Bank Angle Regulation Task and Piloting Technique

## Verbal Description<sup>71</sup>

When a deviation from the desired heading occurs, refer to the attitude indicator and smoothly establish a definite angle of bank which will produce a suitable rate of return. As a guide, the bank attitude change on the attitude indicator should equal the heading deviation in degrees not to exceed 30 deg. (For example, if the heading deviation is 10 deg, then 10 deg of bank would produce a suitable rate of correction.) This guide is particularly helpful during instrument approaches at relatively slow airspeeds. At higher true airspeeds, a larger angle of bank may be required to prevent a prolonged correction. A correction to a heading deviation of 2 deg to 5 deg may be accomplished by application of rudder.

## Feedback Control Description

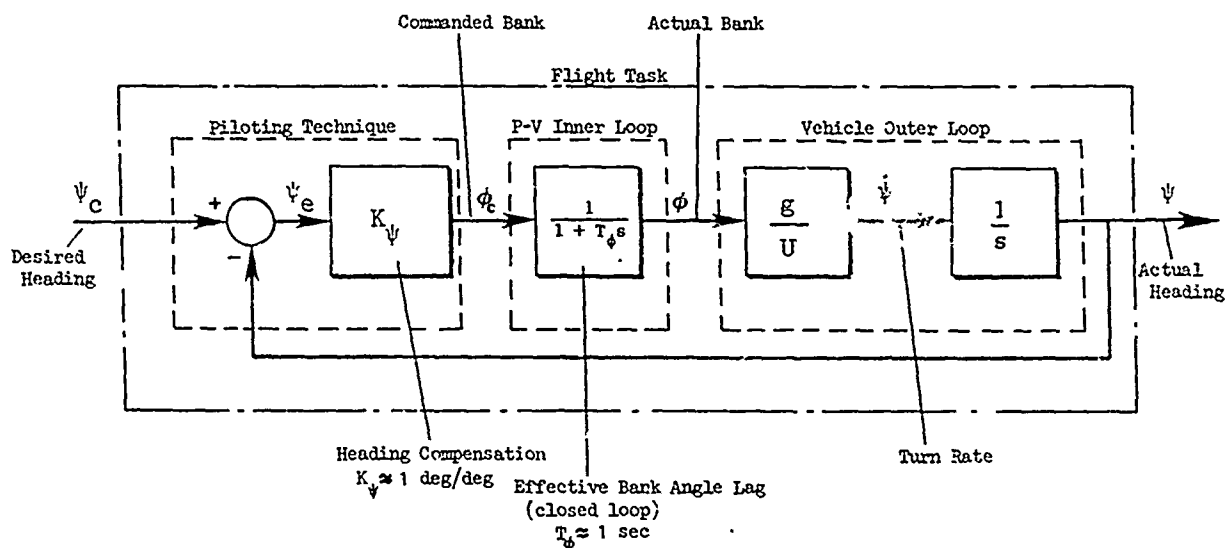


Figure 14. Heading Regulation Task and Piloting Technique

<sup>71</sup> Anon., Instrument Flying, 1979, op cit, p. 2-13.

## Verbal Description<sup>72</sup>

To enter a turn, you should refer to the attitude indicator while applying smooth and coordinated control pressures to establish the desired angle of bank. Bank control should then be maintained throughout the turn by reference to the attitude indicator. Cross-check the heading indicator or turn needle to determine if the angle of bank is satisfactory. Trim may be helpful during prolonged turns to assist in aircraft control.

To roll out of a turn on a desired heading, a lead point must be used. The amount of lead required depends upon the amount of bank used for the turn, the rate the aircraft is turning, and your rollout rate. As a guide, a lead point of approximately 1/3 the angle of bank may be used. With experience and practice a consistent rate of rollout can be developed. A lead point can then be accurately estimated for any combination of angle of bank and rate of turn. Make a note of the rate of movement of the heading indicator during the turn. Estimate the lead required by comparing this rate of movement with the angle of bank and the rate of rollout.

## Feedback Control Description

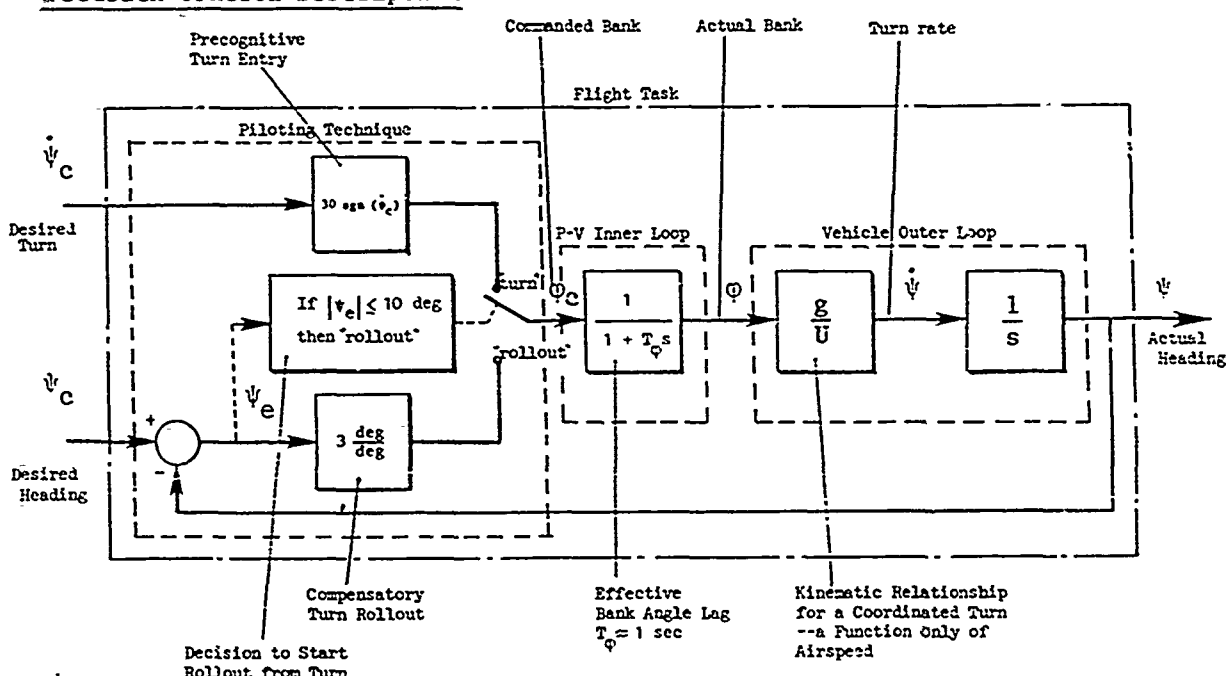


Figure 15. Heading Change Task and Piloting Technique

<sup>72</sup> Ibid, p. 2-13.

## Verbal Description

Adjust pitch attitude by applying appropriate pressure to the longitudinal cyclic stick (or trim button). Monitor pitch response using either the actual horizon or the cockpit artificial horizon.

## Feedback Control Description

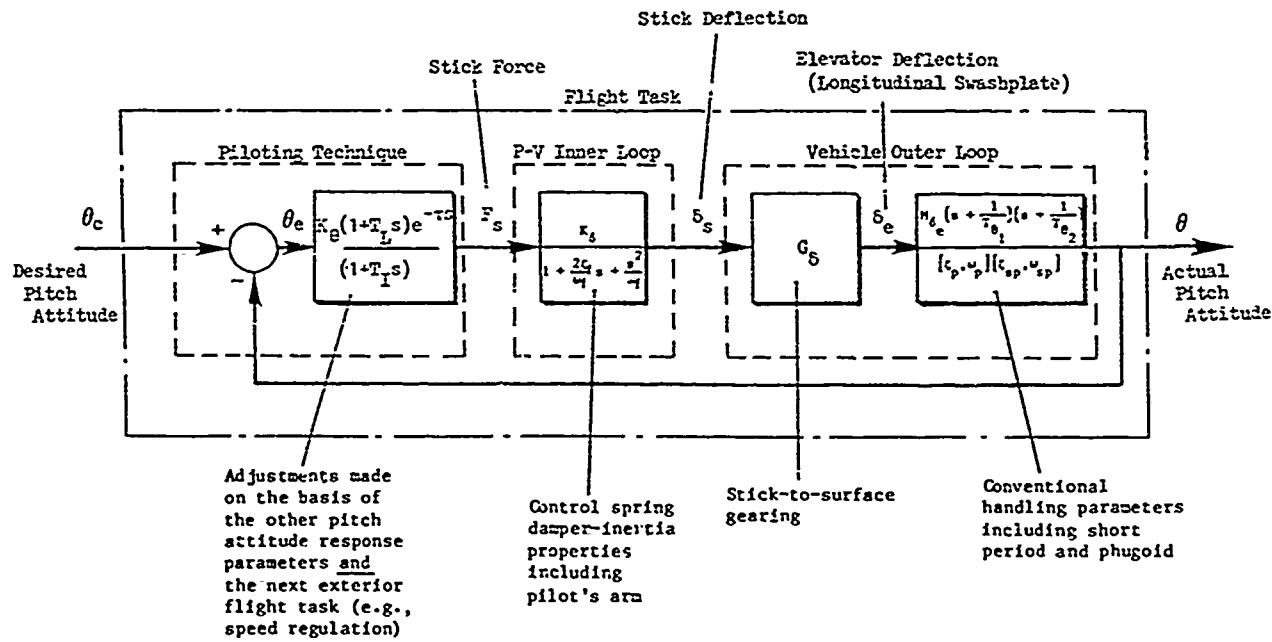


Figure 16. Pitch Attitude Regulation Task and Piloting Technique

### Verbal Description<sup>73</sup>

When a deviation from the desired altitude occurs, determine a rate of vertical correction and apply a power change to correct back to the desired altitude. The correction must not be too large, resulting in the aircraft "overshooting" the desired altitude, nor should it be so small that the correction is unnecessarily prolonged. As a guide, the power change should produce a rate of vertical velocity approximately twice the value of the altitude deviation. For example, if the aircraft is 100 feet off the desired altitude, a 200 feet per minute rate of correction would be a suitable amount. By knowing the present rate of climb or descent and the results to be expected from a power change, you can closely estimate how much to change the power. The adjusted power must be held constant until the rate of correction is observed on the vertical velocity indicator. If it differs from that desired, then further adjustment of the power is required.

### Feedback Control Description

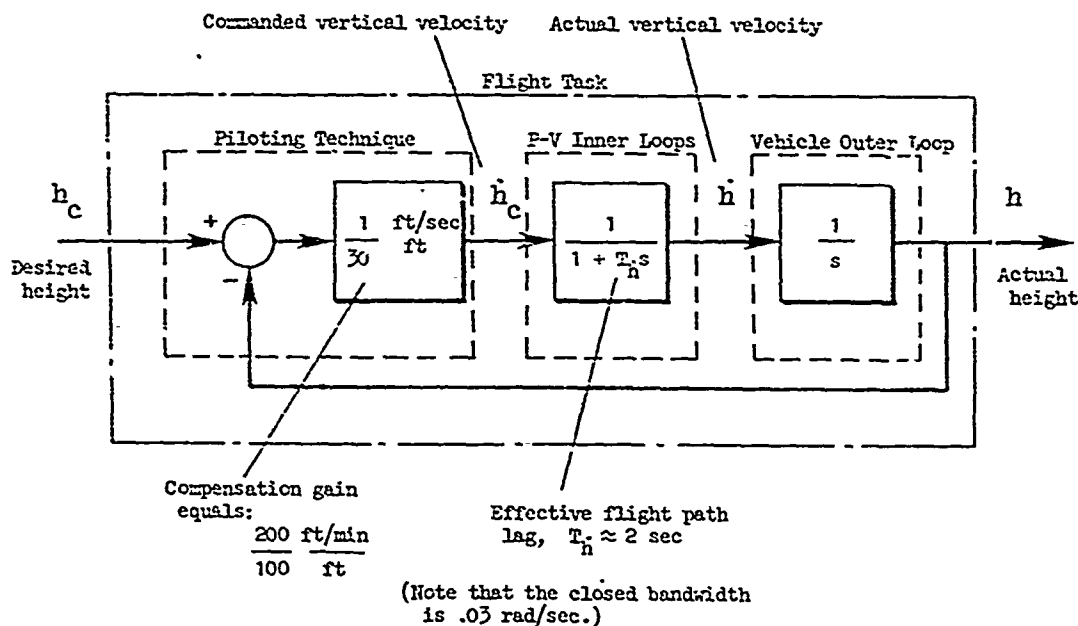


Figure 17. Altitude Regulation Task and Piloting Technique

<sup>73</sup> Ibid, p. 2-11.

#### Verbal Description<sup>74</sup>

Before entering the climb or descent, decide on a power setting and estimate the amount of pitch attitude change required to maintain the airspeed. Normally, the pitch and power changes are made simultaneously.

The power change should be smooth, uninterrupted, and at a rate commensurate with the rate of pitch change. In some aircraft, even though a constant throttle setting is maintained, the power may change with altitude. Therefore, it may be necessary to occasionally cross-check the power indicator(s).

While the power is being changed, refer to the attitude indicator and smoothly accomplish the estimated pitch change. Since smooth, slow power applications will also produce pitch changes, only slight control pressures are needed to establish the pitch change. Additionally, very little trim change is required since the airspeed is constant. With a moderate amount of practice, the pitch and power changes can be properly coordinated so the airspeed will remain within close limits as the climb or descent is entered.

Upon approaching the desired altitude, select a predetermined leveloff lead point. Ten percent of the vertical velocity in feet is a good estimate for the level-off lead point. At the level-off lead point, smoothly adjust the power to an approximate setting required for level flight and simultaneously change the pitch attitude to maintain the desired altitude.

#### Feedback Control Description

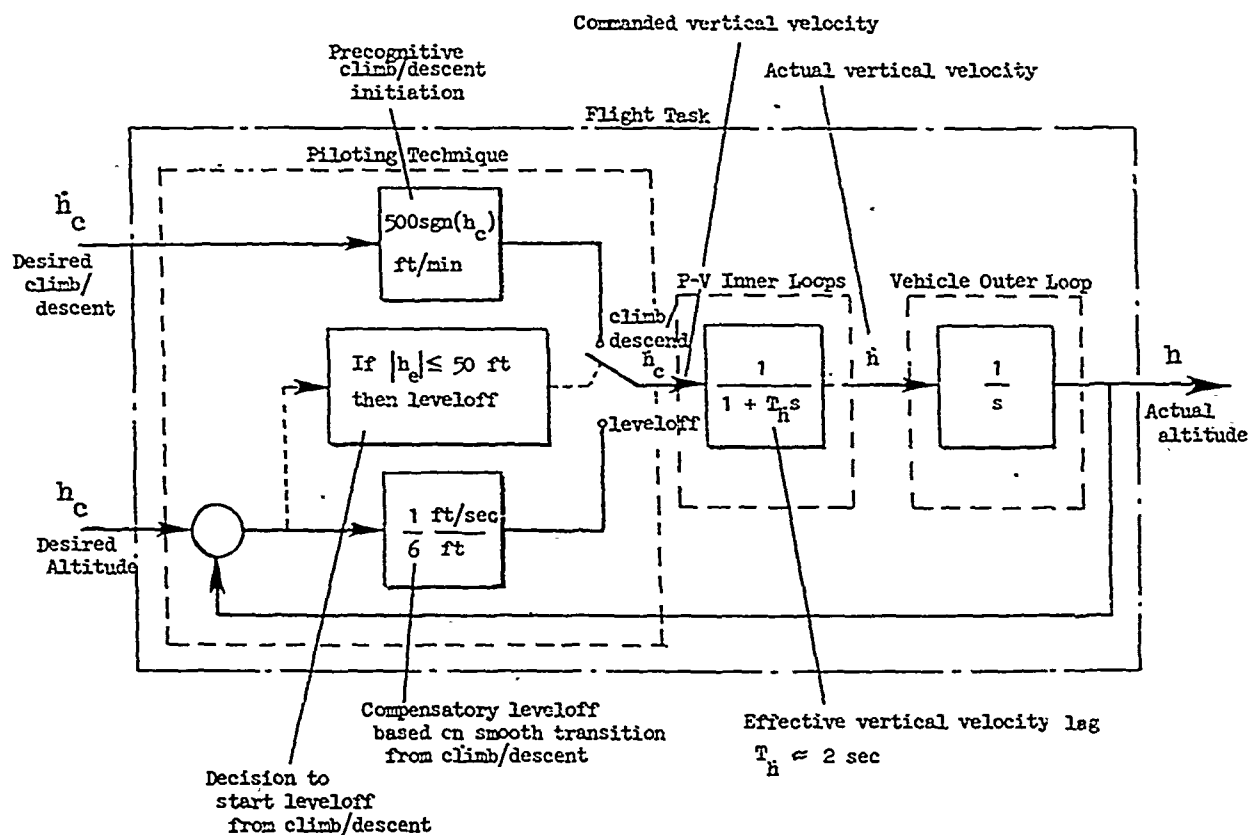


Figure 18. Altitude Change Task and Piloting Technique

<sup>74</sup> Ibid, p. 2-11.



## Verbal Description<sup>75</sup>

In a typical approach, the pitch attitude is 3 to 4 deg for the DC-10. As speed is decreased to threshold speed, the pitch attitude will increase about 1 deg. Landing flare is normally initiated at approximately 30 to 40 ft above the runway surface. In the hypothetical case, if the airplane is flared to a zero rate of descent with idle thrust and a speed of just under threshold at touchdown, the pitch attitude will be 8 to 9 deg. However, with a typical low rate of descent at touchdown, the pitch attitude will normally be 7 to 8 deg. Landing with a 50 flap setting decreases the pitch attitude approximately 1 deg over that for 35 flap. There is ample tail ground clearance for a normal 35 to 50 flap approach and landing, even with the main landing gear struts fully compressed and flat tires. Fuselage contact with the runway will not occur until approximately 14 deg pitch attitude.

## Feedback Control Description<sup>76</sup>

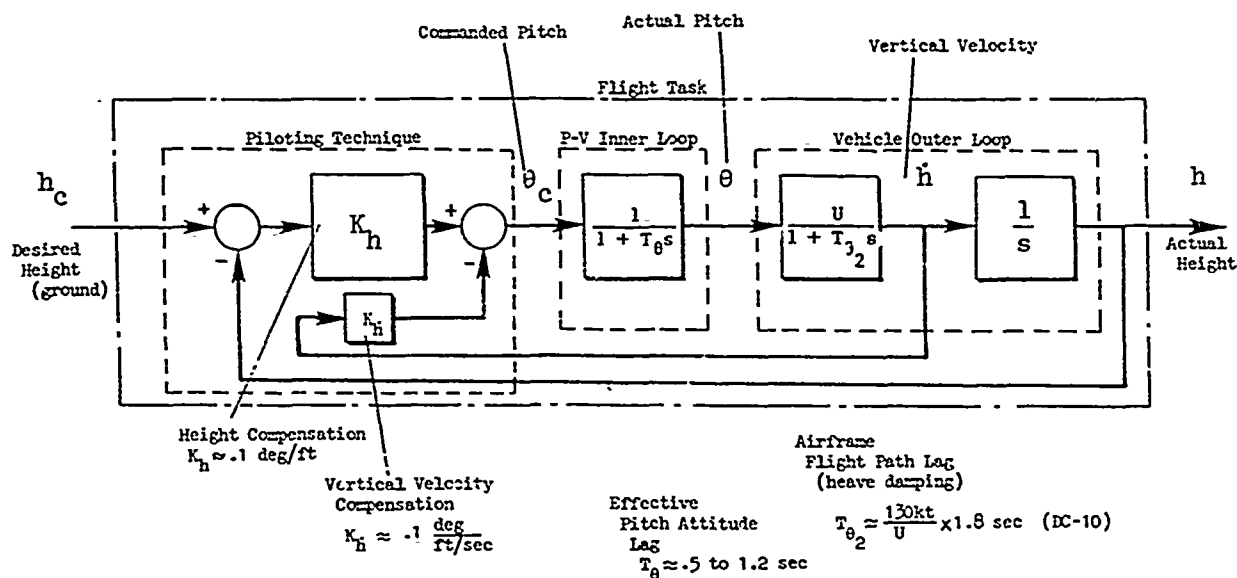


Figure 19. Landing Maneuver Task and Piloting Technique

<sup>75</sup> Anon., United Airlines, DC-10 Flight Manual, Training and Reference, 1973-1974, United Airlines Flight Training Center, Stapleton International Airport, Denver, Colorado, October 17, 1977, p. 4-16.

<sup>76</sup> Heffley, Schulman, Randle, and Clement, 1981, op cit.

### Verbal Description

Effect a speed change Maneuver by simultaneously changing pitch attitude and offsetting flight path upset by suitable use of collective control. Stabilize on the desired new speed through appropriate use of pitch attitude.

### Feedback Control Description

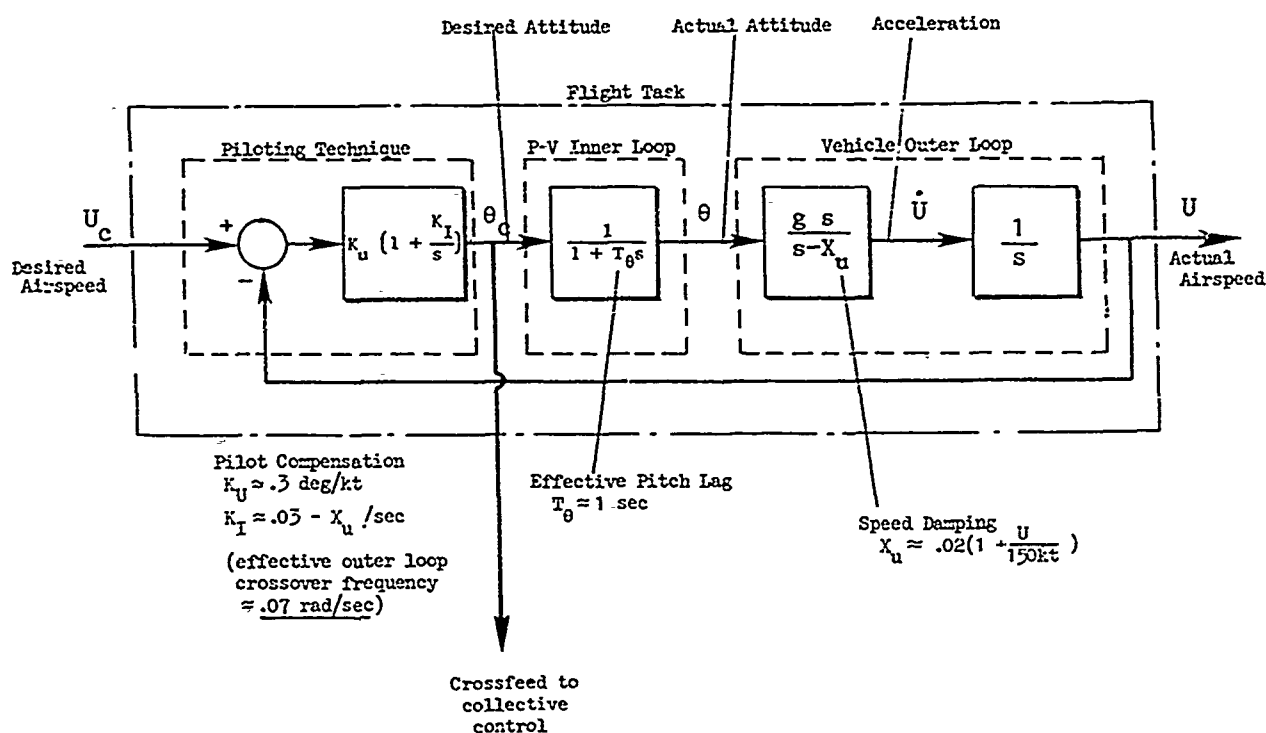


Figure 20. Normal Acceleration/Deceleration Task and Piloting Technique

## Verbal Description

Fly a descending, decelerating visual approach terminating in a 40 ft hover over a landing pad. Avoid abrupt maneuvers. No approach guidance includes only standard aircraft instruments normally used for visual approaches.

## Feedback Control Description<sup>77</sup>

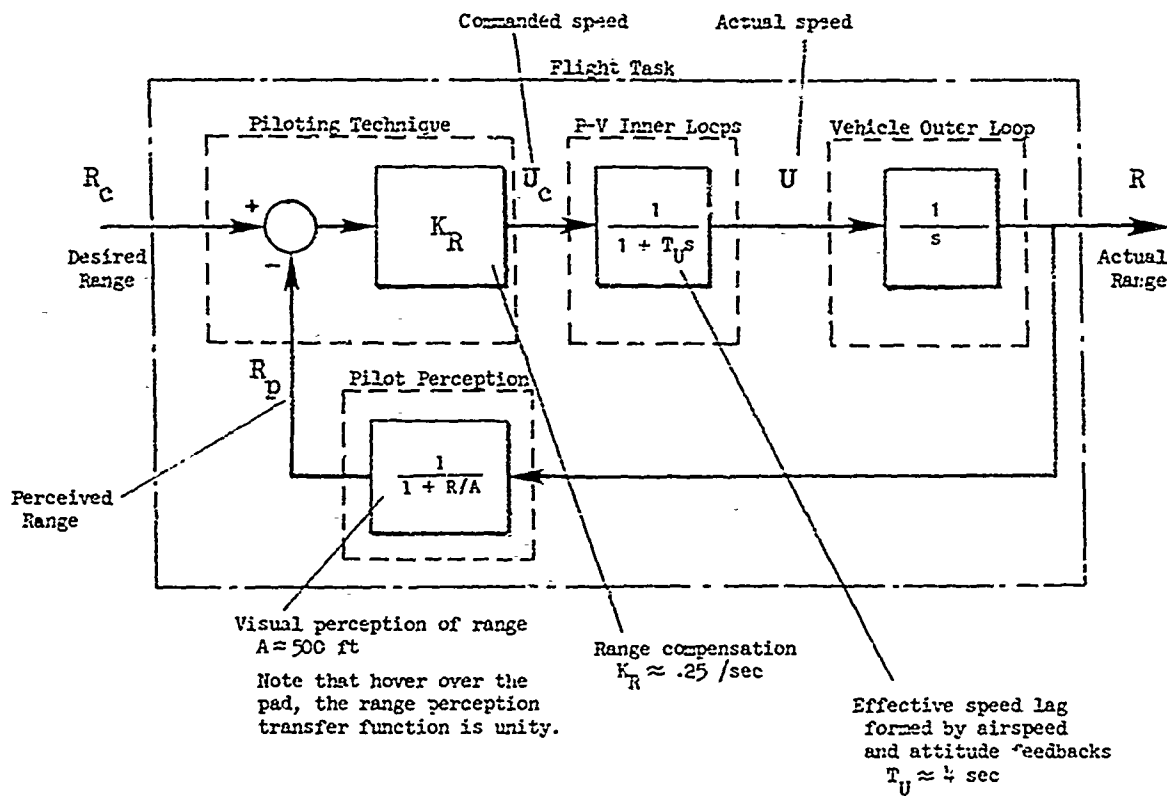


Figure 21. Decelerating Approach to Hover Task and Piloting Technique

<sup>77</sup> Heffley, "A Model for Manual Decelerating Approaches to Hover," 1979, op cit.

### Verbal Description

Halt all forward motion with respect to the terrain as rapidly as possible without ground contact (of the tail rotor) or excessive increase in height

### Feedback Control Description

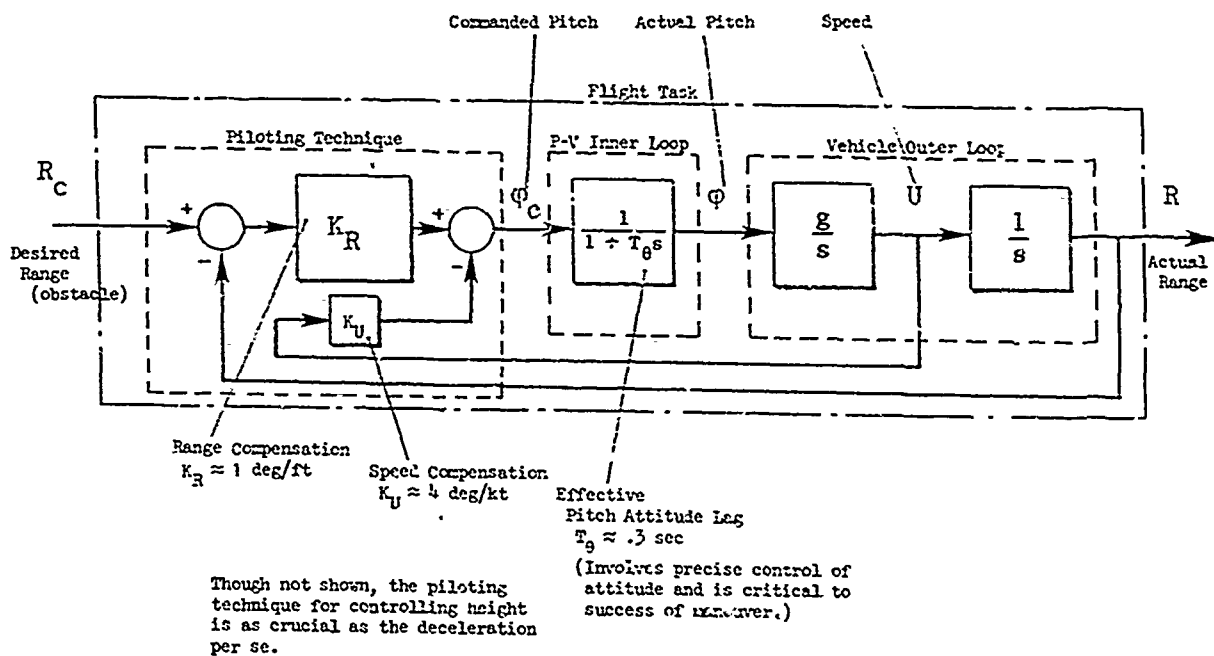


Figure 22. NOE Quickstop Deceleration Task and Piloting Technique

## PILOT MODELING TECHNIQUES

Our next step is to focus on pilot modeling techniques in view of the previous discussions of simulator fidelity and the training missions to be considered. In this section we shall concentrate on how the pilot's control strategy and perception can be modeled.

### PILOT CONTROL MODELING

Pilot control refers not only to the general piloting technique (as discussed already) but also to the adjustment of compensation, selection of available cue information, and adoption of higher levels of control organization. Pilot control can involve a whole "bag of tricks" which is aimed at accomplishing the given task with adequate performance and reasonable workload. The topics which are discussed in the following pages will touch upon some of the more important ideas of pilot control and bring us to a point at which perceptual effects can be addressed.

### Generality of Pilot Modeling

A casual survey of pilot modeling techniques would seem to indicate that it is necessary to restrict ourselves to linear, continuous, and single-loop system models. Yet when we carefully observe the actions of human psychomotor and cognitive behavior in flight, it is clearly non-linear, sometimes more or less continuous, but subject to divided attention, sometimes discrete, and always multiloop. The simple explanation of this dichotomy is that first-order effects can often be effectively and conveniently addressed through use of simplified modeling approaches. Only for special cases is it really necessary to complicate

model features and assumptions, with the examples of thresholds, limiters, variable gains, and cognitive logic illustrated in the previous section.

In fact it is really a matter of necessity that pilot modeling be approached using minimal complexity — only enough to do the job. And the "job" is to gain insight, detect key system parameters, discover sensitive areas, and, in our specific case, to determine motion and visual system characteristics needed to train pilots. It only impedes progress to introduce unimportant pilot model features (or task, vehicle, or disturbance model features) even though many of these features are well known. However let us regard simplification in a far more positive light.

The important and fortunate reality of most pilot modeling applications is that simple models frequently describe pilot behavior within the limits of measurement. Further the same simple models follow the common-sense dictates of good control design, minimization of effort, economy of essential information transfer, and realization of acceptable (but not necessarily optimal) performance to accomplish the task objectives.

Linearization of pilot behavior is an important simplifying assumption for mathematical analysis, but it does not prevent us from introducing any important nonlinear effects. Such effects are merely modeled by linear model forms<sup>78</sup>. One common nonlinearity is the pilot's threshold of indifference to the task objective<sup>79</sup>, an effect easily modeled using a (reduced average) linear gain and a remnant.

Continuous system modeling can be applied under certain conditions even though an inspection of pilot behavior might reveal clear discrete steps in control movement (e.g., throttle) or sampling of visual information (e.g., instrument scanning or head-up/head-down action). Discrete behavior can frequently be described in continuous terms through either simple modeling of cognitive switching or by introduction of an effective

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<sup>78</sup> Graham and McRuer, 1961, op cit.

<sup>79</sup> The perceptual threshold is a lower bound on the threshold of indifference.

system lag which is related to average intervals of discrete activity (e.g., the discrete behavior of a digital computer can often be accounted for using a first-order lag having a time constant equal to the computer frame time). It is also feasible to treat the human controller as a low-rate sample data system for low frequency outer loops such as control of airspeed with throttle.<sup>80</sup>

From the standpoint of constructing minimal parameter models it is frequently desirable to subsume inner loops where possible and, certainly, to neglect any axes which are not directly coupled to the control axis of concern. However, single loop system modeling is the least necessary simplifying assumption, because multiloop analysis procedures are well established and easy to handle with and without computational aids.

With these preliminary statements, let us now develop some notions about modeling control behavior taking full advantage of insights afforded by a simplified, continuous model description.

### Continuous Controller Models

Analysis and measurement (both objective performance, and subjective opinion and commentary) of piloting technique demonstrate that the more important and demanding aspects of the pilot's task are often more continuous in nature than discrete. That is, the pilot performs in a reasonably continuous fashion in response to continuous changes in the aircraft's situation with respect to a mission objective. Thus tight regulation of helicopter position in a hover and maintenance of a prescribed flight path on approach are examples of continuous tasks performed over a period of time in response to continuously changing situations. If

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<sup>80</sup> Heffley and Jewell, Development of a CTOL Piloting Technique Measurement Scheme for a Real-Time Simulator Environment, 1979, op cit.

the continuous task is too demanding of pilot skill, he will be hard pressed to perform other more discrete aspects of his job; e.g., communication with the tower, tuning radios, weapons selection, etc.

These observations motivate a description of the pilot's behavior which can account for the continuous aspects of the pilot's overall task. It is readily observed, for example, that with some aircraft he has a difficult time; with others he can fly without significant subjective effort — in both cases we are supposing that the task goals (e.g., regulating to a desired flight path) are identical. The difference, in this example, is related to the nature of the aircraft's responses to the pilot's controls. What is required is a mathematical model which can account for such influences on pilot opinion and behavior as well as being predictive of pilot continuous task performance. If, in addition, the model is consistent with what is known of the pilot's perceptual, cognitive, and neuromuscular capabilities, considerable confidence is gained in applying it to situations which have not been precisely replicated in previous experiments.

In the continuous piloting task, the pilot is performing as part of a closed loop control system consisting of himself and the aircraft he is flying, and acted upon by environmental influences. His control activity and the external environment cause aircraft motions which he perceives either directly (i.e., from his field of view outside the cockpit and from his vestibular, proprioceptive, and kinesthetic senses) or indirectly from panel-mounted or head-up displays. He responds to these motions by appropriate deflections of the control manipulators in the cockpit so as to achieve task goals — minimize path error, maneuver to a new heading, etc.

### **Classical and Modern Control Theory**

Control system theory offers means by which pilot behavior in closed loop systems can be modeled, measured, and analyzed. "Classical control theory" models the pilot as a combination of sensing, organizing,



equalizing, monitoring, and actuating elements (the choice of words comes from control technology) which are themselves arranged or organized in such a way as to be consistent with what is known of these human capabilities and limitations as well as with the measurable performance of the aircraft and pilot in combination. "Modern control theory" accounts for the possible complexity of this organization by describing the pilot in terms of observers, estimators, control laws, and effectors — the terms are likewise those of the control systems specialist. In either case the behavior being described is the same and either model can be used successfully to the extent that it adequately accounts for pilot behavior as noted in past experiments.

Classical control theory employs isomorphic structural models of pilot behavior, whereas modern control theory employs algorithmic models of pilot behavior<sup>81</sup>.

An isomorphic structure refers to having a form much like that of the human operator or the operator's organizational structure. Isomorphic can apply to neuromuscular, sensory, and equalization functions such as shown in rather general terms in Fig. 23<sup>82</sup>. Taken on a larger scale, it can also apply to a basic task-dependent loop structure as demonstrated earlier in Figs. 8 and 9 for two common aircraft maneuvers.

The algorithmic psychomotor behavior structure supplies (e.g., Fig. 24) the various organizational units which are, in turn, identified or measured by any suitable identification method — parametric or non-parametric, time or frequency domain.

An algorithmic model structure is, in some ways, an abstraction of psychomotor behavior and is based on the notions of optimal control and optimal estimation, i.e., modern control theory. Typically this form of

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81 McRuer, Duane, "Human Dynamics in Man-Machine Systems," Niemi (Ed.), A Link Between Science and Application of Automatic Control, Proceedings of Triennial World Congress of IFAC, 4, Pergamon Press, Elmsford, New York, 1979.

82 Ibid.

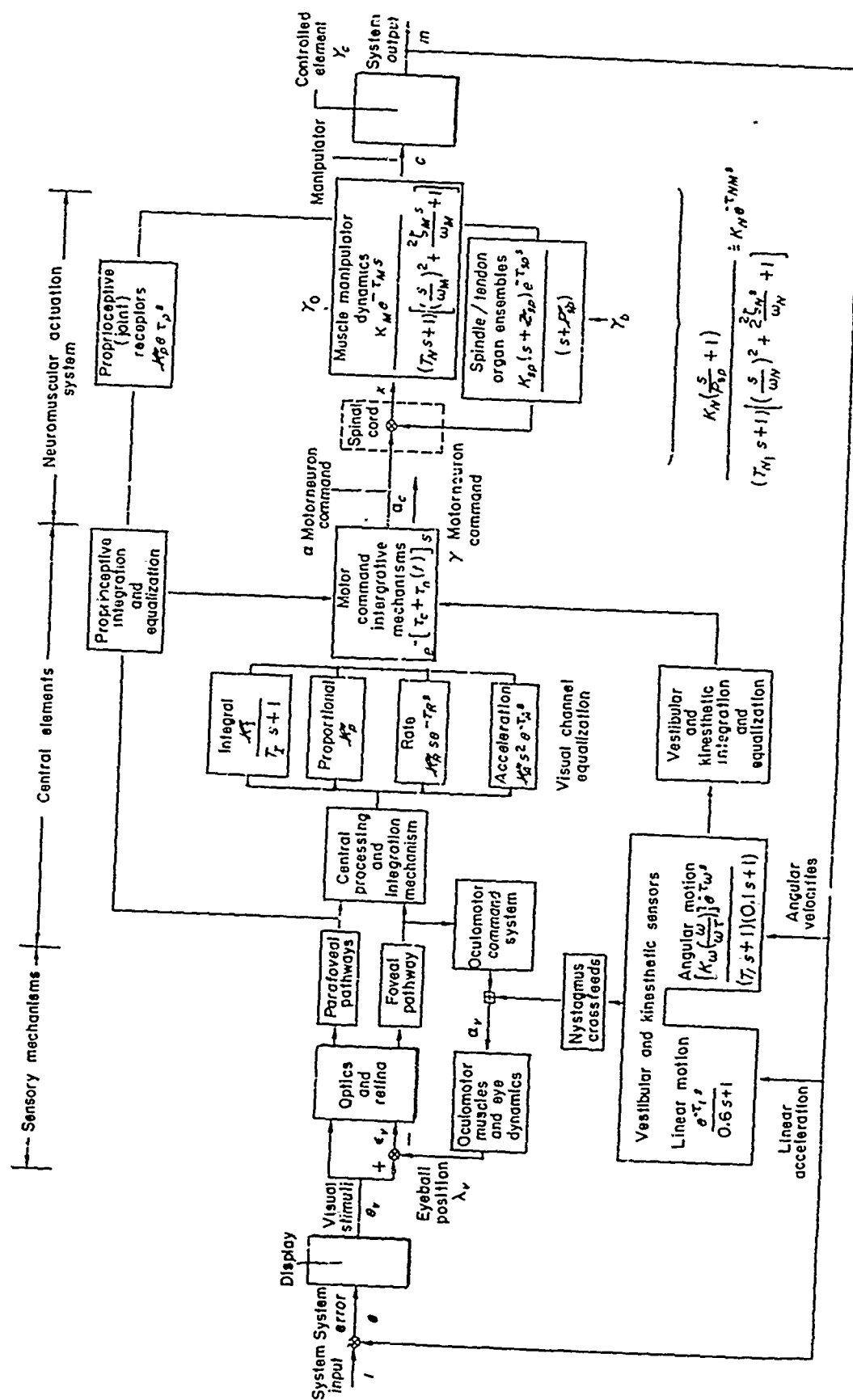


Figure 23. Structural Isomorphic Model of Man-Machine System

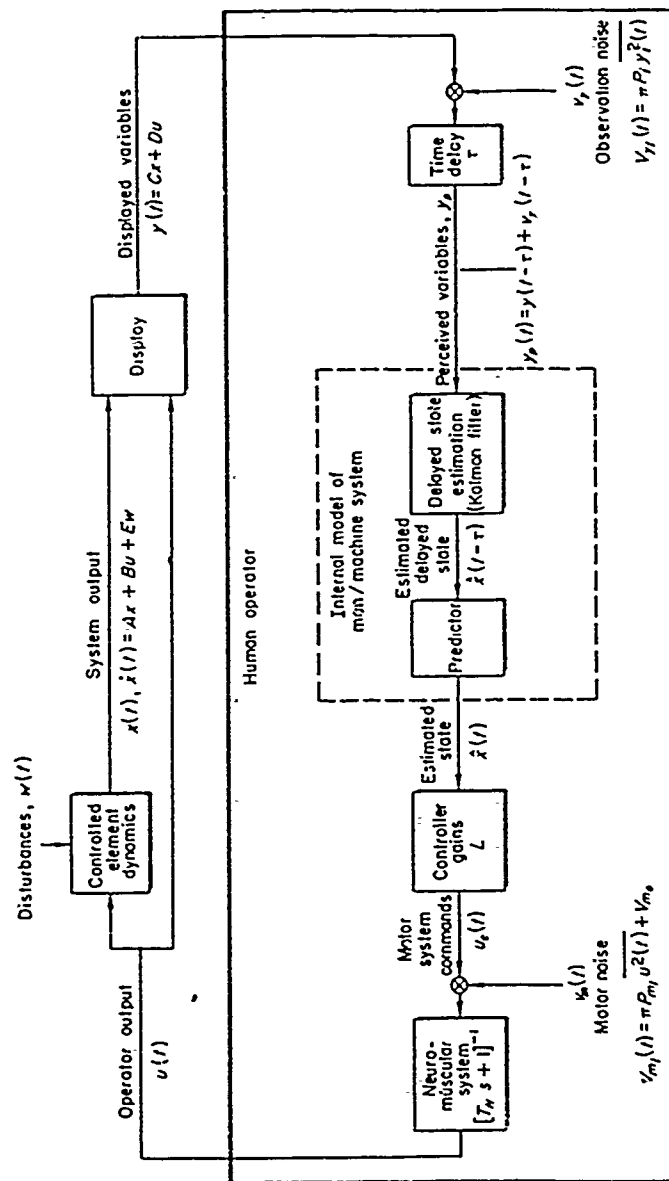


Figure 24. Algorithmic (Linear Optimal Control) Model of Man-Machine System

model expresses the human operator's adaptive control (motor) behavior as an optimal controller which makes use of all system states and controls in such a way as to minimize some form of cost function. Those state variables which are assumed to be perceived are operated on by an optimal estimation process (Kalman filter) in order to generate the needed states for the control process.

Three areas of difficulty of the modern control theory algorithmic model approach regarding psychomotor behavior are given in McRuer<sup>83</sup>. These are, briefly stated:

- The human operator must contain essentially complete knowledge of the man-machine characteristics, i.e., be a complete internal model. Although this might be plausible at the precognitive level of skill development, it is incompatible with what we know about the compensatory level.
- Identification from experimental data is difficult.
- A cost function appropriate to a particular task must be available.

Some other considerations regarding the use of optimal control models (OCM) include:

- The overall pilot-vehicle-disturbance system can be modeled in compatible mathematical terms, but the OCM formulation does not easily permit the simplification advantage of frequency partitioning or decoupling of tasks.
- Application of the OCM procedure is tied to minimization of error, but there is no allowance for non-optimal piloting techniques which may be based on rules-of-thumb or other training techniques.
- The OCM pilot tends to predict "pursuit" behavior, a stage generally corresponding to a high level of skill development, but other stages may not be easily addressed.

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83 Ibid.

Nevertheless algorithmic models may be appropriately and successfully applied to represent the human operator's cognitive perceptual organizing and activity-supervising processes. The process is the Successive Organization of Perception (SOP) developed by Krendel and McRuer<sup>84</sup> and McRuer, et al.,<sup>85</sup> and summarized in McRuer and Krendel<sup>86</sup>. Most of the observed "continuous" manual control behavior falls into relatively few archetypical categories from which logical criteria can be employed to select the most appropriate organizational category, given a task, an environment, and the circumstances attending the operator. One model for the perceptual organization process would be an active off-line supervisory monitor which identifies the conditions that currently exist, selects and activates some most appropriate organizational structures for behavior, monitors the result, and reselects a new or modified organizational structure when necessary or when further information is identified as a result of the initial operations. Appropriately this has been termed the metacontrol<sup>87</sup> system<sup>88</sup>. A simplified diagram of such a metacontroller is given in Fig. 25. Other preliminary work on algorithmic models for these cognitive perceptual organizing and activity-supervising processes are given in McRuer, et al.<sup>89</sup>. Thus algorithmic models should be used where they are best suited (for logical functions), while classical isomorphic structural models are used where they are most efficient (for well-defined

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84 Krendel and McRuer, 1960, op cit.

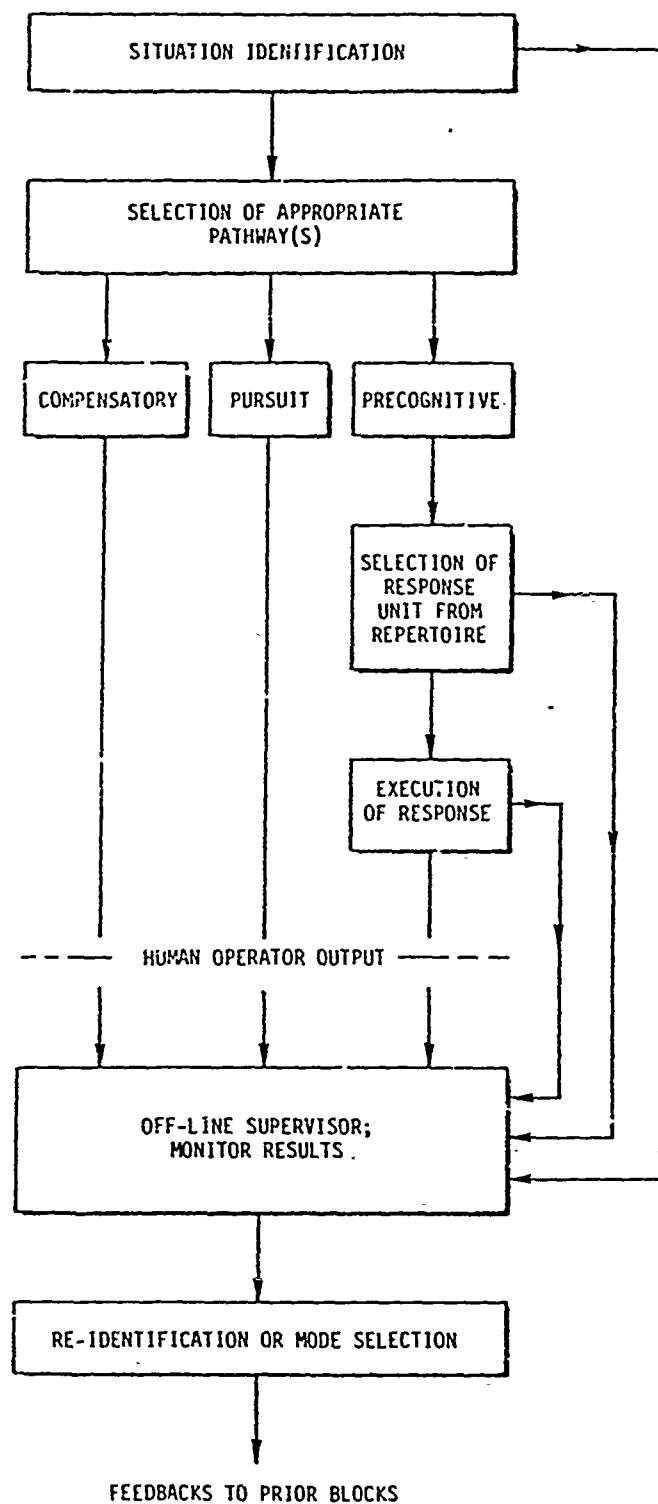
85 McRuer, D. T., et al., New Approaches to Human-Pilot/Vehicle Dynamic Analysis, AFFDL-TR-67-150, February 1968.

86 McRuer and Krendel, 1974, op cit.

87 Metacontrol = the human's activity-supervising control, transcending the various directly involved systems such as the perceptual, central, and neuromuscular systems (from Greek "meta" meaning "involved with changes").

88 Sheridan, 1962, op cit.

89 McRuer, et al., 1968, op cit.



Simplified Metacontroller for Successive  
Organization of Perception

Figure 25. Flow Diagram for SOP Operations

continuous tracking or stimulus-response situations which are subject to divided attention).

In what follows the classical model is chosen to represent the psychomotor activities of the pilot. The initial emphasis in this model is on the pilot's response to visually-derived information — this is where the data base is largest. Later the model will be amended to account for the pilot's ability to sense and use motion information in flying tasks.

### **Pilot Compensation and Adjustment**

The mathematical models which quantify pilot behavior in continuous control tasks take into account two kinds of system requirements:

- Guidance and control requirements which are related to system stability and the capability of following a desired path or executing a desired maneuver.
- Pilot-centered requirements which express the abilities and limitations of the human pilot.

The first set of requirements comprises those which depend upon the task being performed and are independent of the fact that the pilot is human. Aircraft angular and linear motions are sensed and used in closed feedback loops to develop, through appropriate weighting and equalization, the throttle, control stick, pedal, and collective (if the aircraft is a helicopter) deflections that guide and control the aircraft. The choice of which aircraft motion quantities to use and what their relative weighting and equalization must be to achieve system stability and path following capability are all guidance and control requirements which would exist even if the pilot were to be replaced by a complex and elaborate machine.

The second set of requirements comprises those which arise because the pilot is indeed a human being. In spite of his capabilities, he has

certain limitations — he can perform only a limited number of tasks at the same time. The kind and degree of equalization applied to the perceived vehicle motions is likewise limited. Further his control activity is not completely correlated with the aircraft motions — it contains uncorrelated activity — noise to the control engineer, remnant to the human performance researcher. In short the pilot-centered requirements are largely those which are imposed by human limitations<sup>90</sup>.

Among these limited capabilities is the ability to generate lead equalization based on visually perceived aircraft motions. This capability forms an essential part of the human perceptual basis for vehicular guidance, especially in the vicinity of the ground plane. There the relative velocity between helicopter and terrain may be so low as to inhibit the perception of "streamers" which otherwise play a more significant role in visual judgment of aircraft motion<sup>91</sup>. If the motions were presented on a panel instrument, a human factors engineer would think of adding "quickening" to the display — equivalent to one form of lead equalization —

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90 Exceptions are those pilot-centered requirements which are imposed by human capabilities such as adaptation and learning, both of which are at present hardly imitated by machines in their infancy. Learning expresses a human organizational capability in successive encounters with the same environment, whereas adaptation expresses a human organizational capability in an encounter with a new environment.

91 Gordon, D. A., "Perceptual Basis of Vehicular Guidance," Public Roads, 34, 1966, pp. 53-68.

Calvert, E. S., "The Theory of Visual Judgments in Motion and Its Application to the Design of Landing Aids for Aircraft," Transactions of the Illuminating Engineering Society, 22, 1957.

Havron, M. Dean, Information Available from Natural Cues During Final Approach and Landing, Human Sciences Research, Inc., Report HSR-RR-62/3-MK-X, March 1962.

Naish, J. M., "Control Information in Visual Flight," Proceedings of the Seventh Annual Conference on Manual Control, NASA SP-281, June 1971 (also McDonnell Douglas Paper No. 5921).

Grunwald, A. J., and S. J. Merhav, "Vehicle Control by Visual Field Cues," IEEE Transactions, SMC-6, 1976, pp. 835-845.



thereby relieving the pilot of this burden by matching, in a limited sense, the requirements of the task to the pilot's capabilities. At the same time this change in the display might obscure from the pilot that which he calls status or situation information. In this example the state of the motion variable is obscured to an extent depending upon the quickening added to the signal.

Another means of providing lead equalization is to allow the pilot to sense the aircraft motions via his vestibular senses — the semicircular canals and utricles. Observation of pilots in simulators suggests that lead equalization generated by this means comes at less cost (subjective workload) than that derived purely on the basis of visual information — a given level of task performance in a moving base simulator comes easier than if the simulator were on a fixed base.

All of this is well known to the pilot training community. What is important for present purposes is the ability to quantify this behavior in a mathematical model. In fact there is a hierarchy of such models which vary in their elaboration of detail, in their application to specific questions, and so on. Here we shall present a basic model which illustrates most of the concepts involved. For the moment we shall ignore the vestibular aspects and consider visually-perceived information only.

The human pilot, when treated as a set of elements in a larger feedback control system comprised of pilot and aircraft, can be modeled as follows:

- A set of describing functions expressed in terms of a number of parameters.
- A set of adjustment rules for the parameters which depend upon the task and the controlled element (aircraft).
- An additive noise, or remnant, in the pilot's output which accounts for those portions of his response not correlated with his input; i.e., not accounted for by the describing functions operating on the input "signals."

The term describing function comes from automatic control theory. Describing functions are used to express the linear properties of nonlinear elements. The term's use in the context of human response description serves to emphasize that a complex, nonlinear element is being approximated linearly for purposes of quantification in the particular situation.

The describing function is a frequency dependent function which, in its most complete form, contains gains, perceptual and indifference thresholds, time delays, equalizers, and neuromuscular dynamics. The perceptual and indifference thresholds are of paramount importance in the present context; i.e., determining minimal levels of visual and motion stimuli to train flight skills in a simulator. Usually, however, the thresholds are higher-order effects that can either be ignored when the inputs are large or accounted for approximately by using decreased average pilot gain. The neuromuscular system dynamics are based on very high frequency data, and can be approximated at the mid-range of frequencies of interest in flying as a first-order lag or, even more simply, as an increment in the time delay.

#### Crossover Model

The adjustment rules for pilot describing function parameters have been derived from experimental data for a wide variety of single-loop and multiloop control tasks. These data show that a relatively simple rationale exists for the equalization adopted by the pilot. It is called the "crossover model"<sup>92</sup>.

According to this model, given a controlled element having describing function  $Y_c$ , the pilot adjusts his describing function,  $Y_p$ , in each loop such that the open-loop combined describing function,  $Y_p Y_c$ , approximates a frequency-dependent function of the form:

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<sup>92</sup> McRuer and Krendel, 1974, op cit.

$$Y_p Y_c \approx \frac{\omega_c}{s} \quad (1)$$

in the vicinity of the gain crossover frequency,  $\omega_c$ , for that loop<sup>93</sup> This form should be more correctly written to include a pure time delay,  $\tau_e$ , which represents the pilot's effective neuromuscular lag as well as any high frequency vehicle response lags.

To accomplish this end result, the pilot must tailor his describing function,  $Y_p$ , to the specifics of the control situation.  $Y_p$  is expressible in terms of the following parameters:

- Time delay,  $\tau$ , which accounts for the latencies due to perception, interpretation, and neuromuscular actuation.
- Pilot gain,  $K_p$ , which determines the amount of control correction for a perceived level of state error.
- Equalization, which tailors the form of the pilot's response to suit a given vehicle's handling dynamics.

The crossover model (Eq. 1) states that if the describing function,  $Y_c$ , has more lag than the describing function,  $K/s$ , in the vicinity of the desired gain crossover frequency,  $\omega_c$ , then some pilot lead equalization (anticipation), will be required; while if  $Y_c$  is more like  $K$  than  $K/s$ , some pilot lag equalization will be used to achieve good pilot/vehicle system response and performance. The parameters,  $\omega_c$  and  $\tau_e$ , in the cross-

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<sup>93</sup> The describing function  $1/s$  or sometimes " $K/s$ " is a mathematical form representing an integration with respect to time. A system having such dynamic properties is called a "rate system;" i.e., a step input results in a constant rate of change output, at least over a reasonable spectral range. One example of a  $K/s$  system would be the airspeed response due to a pitch attitude change in a helicopter — a unit nose-down pitch change results in a nearly-constant forward acceleration over a large speed change.

over model depend on the frequency content (bandwidth) of the disturbance or desired path (maneuver) input and on the pilot equalization. Data show that the crossover frequency is greatest and the pilot time delay is least when his equalization is a low-frequency lag. At the other extreme,  $\omega_c$  is the least and  $\tau_e$  the greatest when the pilot must generate low-frequency lead. In fact the major "cost" of equalization is this increase in time delay. Both  $\tau_e$  and  $\omega_c$  will vary with pilot skill and level of attention to the control task. Experimentally-based values for the crossover model parameters for several dynamic forms and input bandwidths are given in McRuer and Krendel<sup>94</sup> as well as elsewhere.

The complete pilot description includes the remnant. The major sources of this "noise" in the pilot's output appear to be caused by non-stationarity in his behavior, divided attention, and low frequency lead generation within the visual modality. When his output is expressed as a power spectrum, the remnant can be considered as pilot-induced broadband random noise added to the input-correlated portion of the signal. For aircraft control situations involving reasonable flying qualities, the remnant will be small relative to that part of his response involved in making a maneuver or in regulating against an external disturbance.

### Levels of Skill Development

The simple crossover model given above is diagrammed as shown in Fig. 26. It describes pilot behavior in single-loop compensatory control tasks and in the outermost loop of multiloop compensatory tasks. In this system structure, the pilot is controlling a single task-related response variable with a single control by operating only on the perceived error. A typical example of such behavior would be regulation of vehicle attitude in a gusty environment as represented by a fixed base simulator (no

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<sup>94</sup> Ibid.

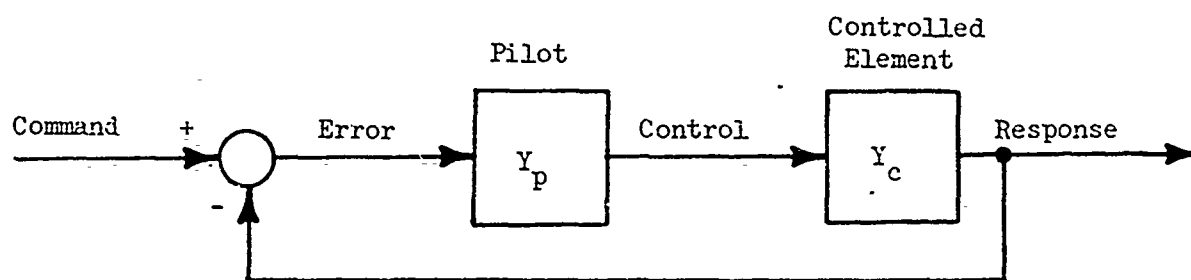


Figure 26. Compensatory Pilot Model

motion). The pilot cannot preview what is coming and can only respond to the developing error as it becomes manifest on his displays or in the simulated visual scene.

The data base which quantifies the single loop compensatory pilot model consists primarily of describing function measurements of well-trained pilot subjects. This qualification significantly reduces the variability which would otherwise be quite prevalent in the data base. Pilots exhibit quite remarkable uniformity of compensatory behavior when the task goals are well defined and the pilot is well trained. There are, of course, individual differences in ability. Some individuals can achieve somewhat better performance than the average through reduced time delay and increased lead generating capability.

The compensatory model is fundamental from a variety of standpoints. Complex multiple-loop tasks involving several controls and responses can be represented by repeated applications of the crossover model. More important for purposes of the present discussion is the fact that the model represents the earliest stage of psychomotor skill development — in the beginning, the pilot regulates against errors and is unable to take advantage of other indicators of system behavior available to him in a rich perceptual environment. Finally it represents the form of behavior to which the pilot reverts when confronted with an unfamiliar or stressful situation wherein more skilled behavior and/or perceptual patterns break down for one reason or another.

Higher levels of psychomotor skill are possible when the pilot can take advantage of additional information available to him. These can be represented by more complex pilot models. There is a hierarchy of such models used to represent various levels of psychomotor skill development. These have been organized according to the degree of information exploitation and formalized in the theory of SOP. In this organization, the compensatory model occupies the lowest position, followed by the pursuit, and finally the precognitive models representing the highest level of skill.

Figure 27 is a simplified diagram of the pursuit model, so-called because it typifies the classic situation where target motion (the input command) is perceived as separate and distinct from the aiming error. If quite familiar with the response properties of the controlled element (his own aircraft), he can operate only on this input and generate control activity which will result in responses having very little error. In effect his describing function (operating only on the command) is given by  $Y_{p_1} \approx 1/Y_c$  such that  $Y_{p_1} Y_c \approx 1$ . At the same time he will respond to the residual errors with the appropriate compensatory behavior, represented in Fig. 27 by  $Y_{p_e}$ .

If, in addition, the pilot is aware of the controlled element's responses, as distinct from the error or the command, he may find it useful to operate on this information as well to improve system performance. In Fig. 27 this is represented by  $Y_{p_m}$ . The most typical example is the pilot's use of vehicle motion, sensed through vestibular, proprioceptive, and kinesthetic senses, to improve upon system performance. Because the information is perceived through a sensory modality other than visual, this model, a special case of the pursuit model, is referred to as a multimodality pilot model.

Unfortunately, quantification of the multimodality pursuit model, the data base is limited to two separate visual and motion channels,  $Y_{p_e}$  and  $Y_{p_m}$ , respectively. Stapleford, et al.,<sup>95</sup> suggest a model in which  $Y_{p_m}$  takes on the known properties of the vestibular sensing apparatus of the human in those cases where the controlled element requires lead equalization. The pilot need not derive his lead from the visual stimuli alone and (need not) incur the resultant "costs" associated with visual lead — increased time delay, higher remnant levels, and so on.

For purely compensatory tasks, i.e., wherein the simpler structure of Fig. 26 is assumed, moving base data are more readily available. These data suggest that with those controlled elements requiring lead

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<sup>95</sup> Stapleford, Peters, and Alex, 1969, op cit.

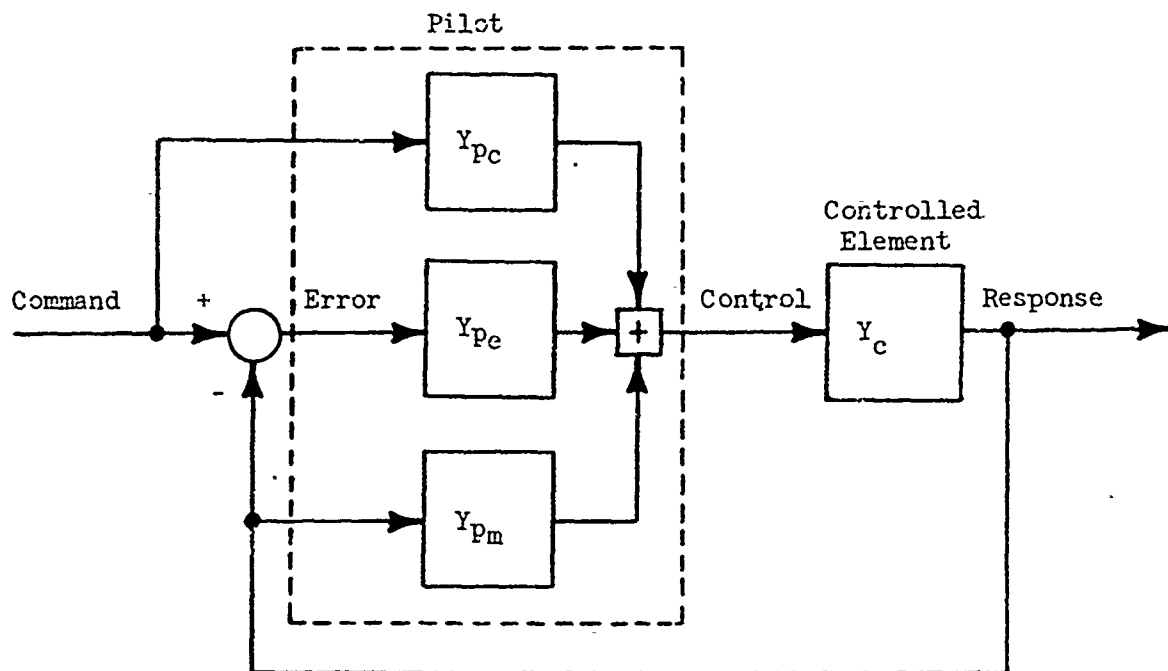


Figure 27. Pursuit Pilot Model



equalization the effect of the motion is to reduce the pilot time delay and increase the available crossover frequency. The continuous task performance is thereby improved (increasing crossover frequency,  $\omega_c$ , means reduced error in following pilot commands or regulating against disturbances). Pilot opinion tends to be more favorable, indicating less subjective workload with motion perception. In sum these data are consistent with the more limited data pertaining to the two-channel multimodality model.

Pursuit level of operation can sometimes be detected by certain describing function signatures. Hess<sup>96</sup> discusses this by exploring analytically the basic pursuit model (Fig. 27) and relating it to various laboratory measurements which reveal pursuit versus compensatory behavior. The nature of pursuit effects is illustrated in Fig. 28 in terms of the combined pilot-vehicle open-loop describing function amplitude and phase characteristics. Note that the symptoms of pursuit behavior are the low frequency amplitude "droop" and reduced phase lag. At crossover the open-loop pilot-vehicle describing function remains close to the form  $K/s$ . Only at low frequencies do the pursuit tendencies appear. This suggests how to detect and measure higher stages of SOP and gives some idea of where it is of some consequence spectrally.

At this point let us make two observations which relate to the above pursuit-level symptoms. First, optimal control pilot models, when used to predict pilot behavior such as described by Curry, et al.,<sup>97</sup> tend to yield a pursuit-level describing function signature. Second, the role of cockpit motion discussed by Hess<sup>98</sup>, whether predicted by optimal or classical methods, tends to be related to low frequency pursuit behavior and not to basic compensatory actions at or near the crossover frequency.

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<sup>96</sup> Hess, Ronald A., "Pursuit Tracking and Higher Levels of Skill Development in the Human Pilot," Sixteenth Annual Conference on Manual Control, MIT, Cambridge, Massachusetts, May 5-7, 1980.

<sup>97</sup> Curry, R. E., W. C. Hoffman, and L. R. Young, Pilot Modeling for Manned Simulation. Volume I, AFFDL-TR-76-124, December 1976.

<sup>98</sup> Hess, 1980, op cit.

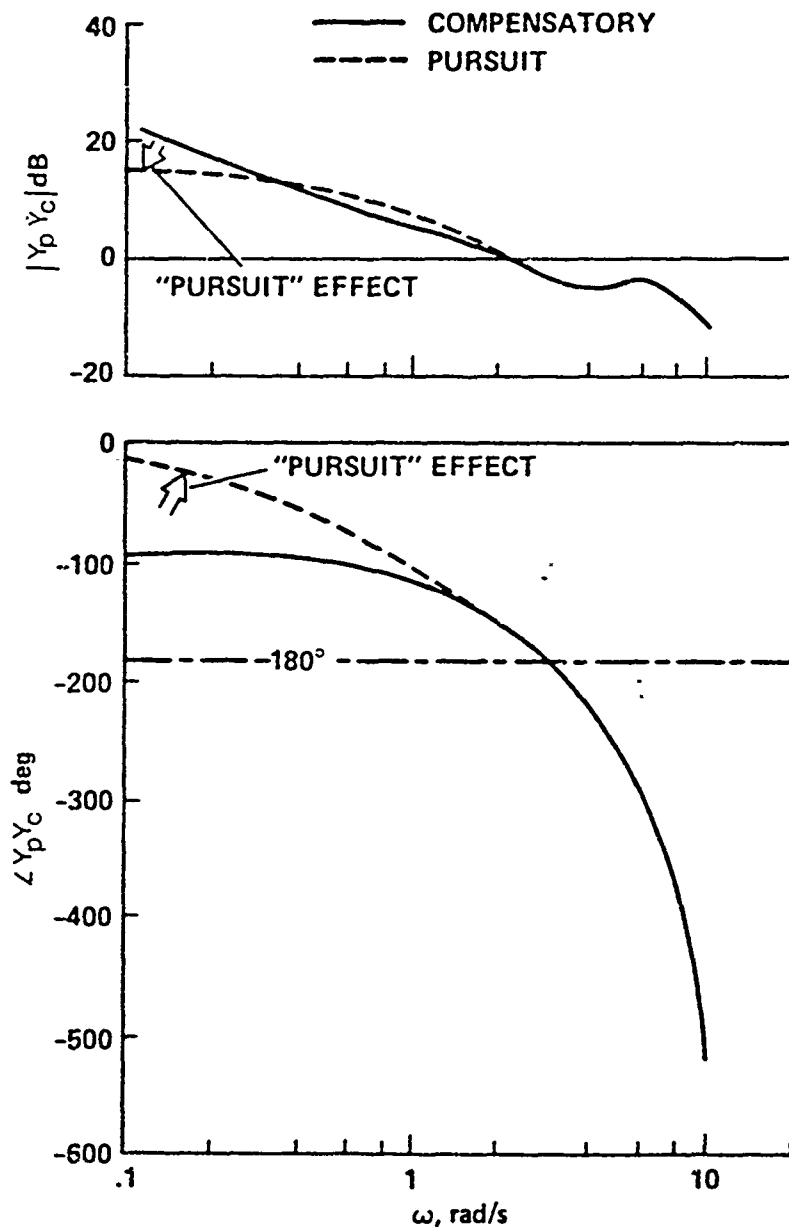


Figure 28. Comparison of Pursuit and Compensatory Model Describing Functions. (Taken From Hess<sup>99</sup>)

<sup>99</sup> Ibid.

Finally, the highest level of psychomotor skill is described by the precognitive model. This model represents those skilled control activities which resemble preprogrammed or self-generated behavior. The pilot acts as though the only information needed, presuming full familiarity with the input command and the controlled element, is the triggering stimulus which tells him when to begin and his sensations of his control movements.

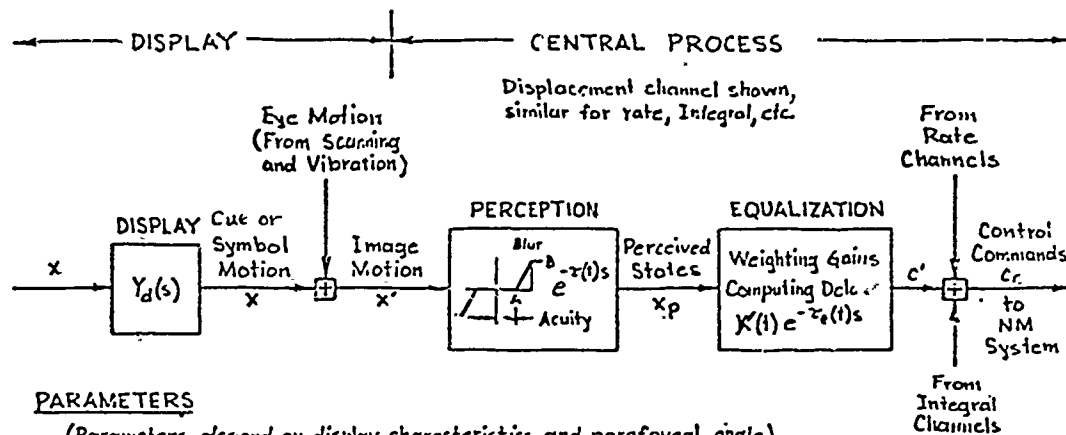
From the standpoint of training, it is the "full familiarity" with the task which must be acquired — in part through simulated aircraft motions. Even though performance in a particular task is known to be precognitive in nature (for well-trained pilots) and thus a task where precise replication of stimuli in all sensory modalities is not necessary for task performance, it is nonetheless required that the stimuli be available to facilitate skill acquisition through the compensatory and pursuit phases of the SOP sequence. In this respect it can be argued that the training simulator has fidelity requirements in excess of those needed in many research simulators — at least if proficiency levels approaching those of trained pilots are to be reached. In the research simulator the pilots are more often than not well up on the training curves for basic and secondary flying skills.

As a consequence motion fidelity requirements analysis using mathematical models of the human pilot will probably concentrate on pursuit models. These models provide the means by which the several training task scenarios can be analyzed for the potential involvement of motion in improving task performance.

### **Perceptual Effects on Control**

Our current approach, illustrated in Figs. 7 and 29, is to separate the operator's perceived states into integral, proportional, rate, and sometimes acceleration signals, each derived and weighted by central nervous system processes. These processes are, however, imperfectly

a. Physical Model for a Typical Perceptual Channel Showing Separation of Display, Perceptual, and Equalizing Parameters



PARAMETERS

(Parameters depend on display characteristics and parafoveal angle)

Gains	Detection Process Delays, $\tau$	Control Gains $K(t)$
Lags	Static & Dynamic Acuity Thresholds, $A$	Computing Delays $\tau_c(t)$
Resolution (Quantization)	Blur & Saturation Limits, $B$	Processing Noise and
Luminance	Observation Noise	Time Varying Parameters

b. Revised Central Process Model, Including Perceptual Processes, Showing Each State Channel Represented by a Describing Function Plus Related Noise

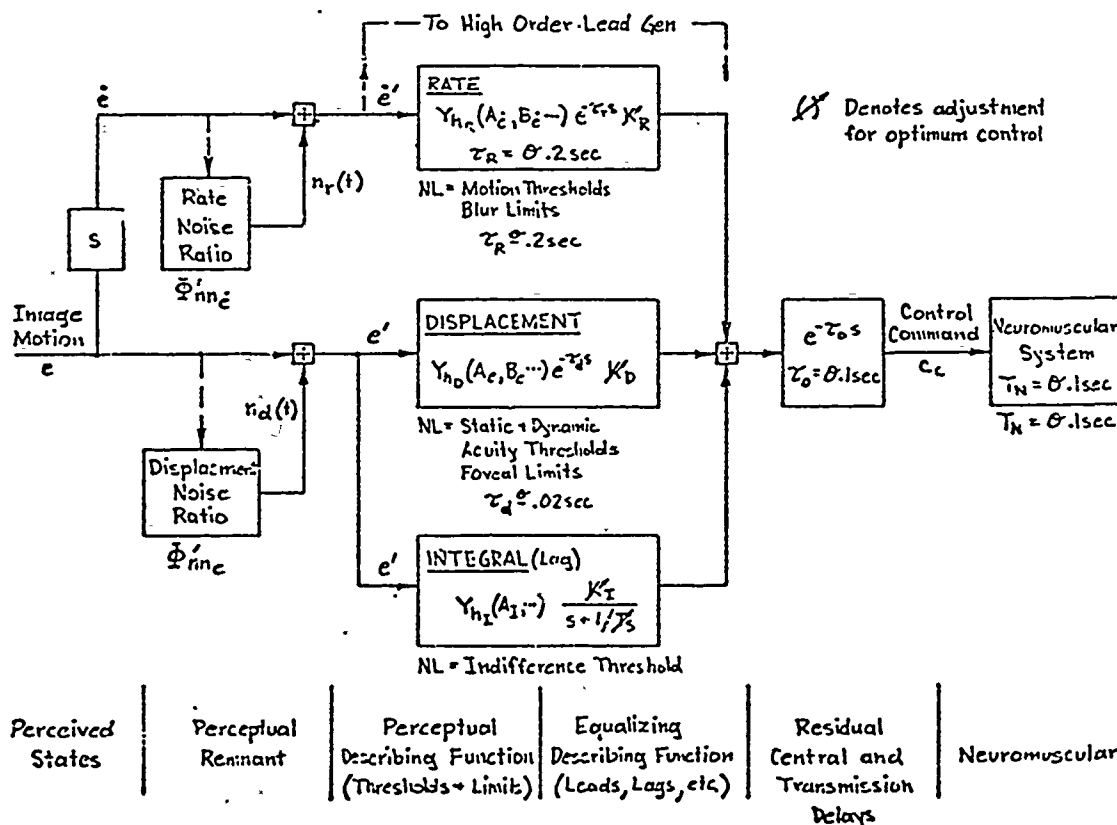


Figure 29. Refinement of Central Process Models for Perception Of Displayed Signals (Non-Scanned Cases)

understood at present. But the lack of determinism in portions of the human operator models under certain conditions is reflected by corresponding variations in the stochastic "remnant" (e.g., observation and motor noise). The "remnant" forms an essential part of the contemporary, quasi-linear pilot models. It is attributable to time-varying time delays, scanning and sampling processes, neuromuscular ("motor") noise, tracking style, and idiosyncratic effects. Among the sources neuromuscular noise is the least important one when investigating multiaxis visual display-related effects. We expect that the adverse perceptual effects of inadequate luminance, resolution, contrast, and symbol motion (threshold and blur limits in Fig. 29a) will be reflected in increased observation noise, as well as in attenuation and time delay in the operator's describing function.

By careful experimentation during the last several years we, and others, have found that such closed-loop perceptual effects can be represented by a nonlinear random-input "perceptual describing function" plus a "processing remnant spectral gradient," both of which depend on the display and perceptual characteristics. On the other hand the remnant spectrum has been found to be nearly invariant when it is normalized by the perceived state displacement and rate — especially the latter. Hence the processing remnant is represented as a multiplicative noise process acting on each perceived state<sup>100</sup>.

When passed around a tracking control loop, the high frequency noise components in the control signal are usually attenuated by the controlled element, and any quasi-periodic components are dispersed, so that the resulting perceptual remnant appears broadband and has stochastically stationary properties. This fact permits a great economy of computation. Because most of the display and perceptual effects tend to have frequency invariant describing functions, and because we can determine only overall effects from any one measurement, it is customary to lump these perceptual remnant effects with the operator's adjustable state-

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<sup>100</sup> McRuer and Krendel, 1974, op cit.

weightings (e.g., rate, displacement, integral) so as to yield an effective set of gains for the operator as shown in Fig. 29b. For our purposes here, however, we will keep the perceptual describing function and remnant separated from the equalization, so as to permit a closer tie-in with associated displayed variables; and because we plan to include the pilot's scanning, sampling, and reconstruction effects on the remnant as well.

## PERCEPTUAL MODELING

### Motion Perception

The material in this section describes and applies the multimodality pilot model to the question of motion fidelity requirements in a training simulator. Motion is necessary for pilot-vehicle performance on the highest levels: it "unloads" the pilot's visual modality by opening up another sensory pathway for control of the simulated aircraft and monitoring of its dynamic behavior.

Distorted motion may compromise skill development, at least for inexperienced pilots, because the pilot has no reservoir of past flight experience upon which to assess the motion "lessons" taught by the simulator. For experienced pilots the fidelity can be compromised more; but, even here, he will not be able to acquire the highest level of skill that can be acquired in flying the aircraft.

Threshold effects are important in modeling sensory processes<sup>101</sup>. Given a threshold effect, it is assumed that motions whose magnitudes fall below the threshold level will not be perceived by the pilot. There are two types of thresholds modeled here. The first is a sensory threshold,

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<sup>101</sup> Hofmann and Riedel, 1979, op cit.

it arises from physical limitations of the organ itself. This threshold type is evident for the semi-circular canals — they are unable to sense angular velocities of magnitude less than  $0.035 \text{ rad/sec}$ <sup>102</sup>.

The second type of threshold is the "indifference" threshold, mentioned previously. This threshold type is evident for specific force sensing. Under normal workload, pilots appear unable to detect specific forces of magnitude less than approximately  $0.1 \text{ g}$ <sup>103</sup>. It is important to note that phrase "under normal workload" in discussions of indifference thresholds. If a subject is asked to concentrate on determining when the sensation of specific force begins, the sensory threshold is found to be approximately  $0.005 \text{ g}$ <sup>104</sup> — the otoliths are very sensitive to stimulation. If the subject is given a task to perform in addition to indicating the onset of a specific force, this "indifference" threshold is found to be much higher than the sensory threshold — approximately  $0.1 \text{ g}$ , as stated above. In the simulation of actual flight scenarios, it is assumed that the indifference threshold will be operative; since the pilot's primary task will not be mere detection of the motion cues but rather an actual flying task. The indifference threshold may be visualized not as a sensory limitation but as the result of an information processing allocation decision made in the central nervous system to weight the primary tasks associated with flying the aircraft more heavily than the task associated with specific force sensing. Although this allocation process is not at all well understood, the resulting threshold effect is easily modeled.

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102 Young, L. R. "Current Status of Vestibular System Models," Automatica, 5, 1969, pp. 369-383.

103 Roark, Marvin, and Andrew Junker, "The Effects of Closed Loop Tracking on a Subjective Tilt Threshold in the Roll Axis," Proceedings of the Fourteenth Annual Conference on Manual Control, University of Southern California, April 25-27, 1978.

104 Young, 1969, op cit.

The perceptual model includes the sensory threshold for angular velocity and the indifference threshold for specific force in the appropriate paths. Figure 30 depicts the model used to implement these thresholds as a mathematical functions. Also the threshold level for each axis is indicated.

An alternate, but indirect, method of treating thresholds in motion perception is to use a "divided attention" model of the pilot's sensors. This technique is involved in the optimal control model employed by Baron, et al.,<sup>105</sup> and Levison and Junker<sup>106</sup> to match rms performance of experimental data obtained from motion simulators. The technique assumes that the pilot spends fractions of time sampling various sensors (e.g., visual, vestibular, tactile). These time fractions are then used to scale noise models of the sensor outputs, and thus to predict rms performance. The method is indirect in that random noise alone is not a sufficient model for a threshold either physically or mathematically. It is also not clear how one systematically sets the values for the various time fractions.

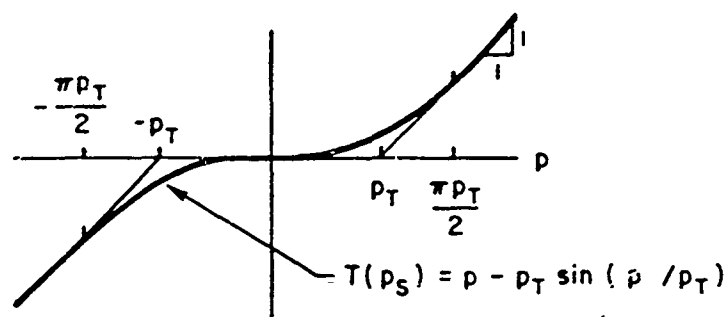
Unfortunately high fidelity motion is very expensive to obtain in ground simulators because of the large linear travel required in the motion base. This suggests that the training simulator can accomplish only part-task training, i.e., for tasks involving motion with high levels of fidelity, the motion amplitudes are necessarily small. For full task training, distortion in the motion sensations must be accepted in a ground simulator, particularly in the military application where the accelerations can be relatively high as compared to the civilian application. This suggests the simulator to be capable of training to a lower level of proficiency, or as a procedural trainer, a "refresher" for experienced pilots. The novice should transition to the aircraft before inappropriate precognitive skills in "flying" the full task simulator are acquired.

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<sup>105</sup> Baron, Lancraft, and Zacharias, 1980, op cit.

<sup>106</sup> Levison, W. H., and A. M. Junker, "Use of a Tilt Cue in a Simulated Heading Tracking Task," Fourteenth Annual Conference on Manual Control, NASA Conference Publication 2060, November 1978.





a) Presumed Form of Indifference Threshold

<u>AXIS</u>	<u>THRESHOLD VALUE</u>
Pitch	2 deg/sec
Surge	0.1 g
Roll	2 deg/sec
Sway	0.1 g
Yaw	2 deg/sec
Heave	0.0 g

Figure 30. Threshold Model and Threshold  
Values for Each Axis  
(Borrowed from Hofmann and Riedel <sup>107</sup>)

<sup>107</sup> Hofmann and Riedel, 1979, op cit.

It is convenient to categorize the kinds of flight motions in three groups<sup>108</sup> according to the difficulty and expense of replicating them accurately on the ground. By "accurately" it is implied that the differences between simulator motions and flight motions are undetectable in the objective results of training with motion in the simulator. Subjectively the differences may be detectable, although acceptable to the pilots. The criteria for judgment of accuracy in motion replication include:

1. The pilot-vehicle task performance in the simulator and in the aircraft are the same.
2. Pilot task adaptation (pilot model equalization, gains, etc.) are the same in the simulator and in the aircraft.
3. Perceptual conflicts and disorientation episodes occur in similar situations, with similar frequency and for the same reasons in the simulator and in the aircraft.

The three categories of flight motion are as follows:

The first comprises those low level, typically high frequency motions which are not manifest in visual displays or simulations of an outside visual scene, and which make modest demands on linear motion base travel. These motions provide a "background" and contribute a sense of realism to the simulated task but are not used in the closed loop control sense. They typically are related to the simulated flight environment: rotor slap, buffet, very low level turbulence (ignorable from the standpoint of control), etc. These motions may be used intermittently as indicators of the simulated flight condition. In any event the fidelity

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<sup>108</sup> Caro considers two basic kinds of motion in a similar discussion of motion fidelity needs. The reader should consult: Caro, Paul W., "Platform Motion and Simulator Training Effectiveness," Proceedings of the 10th NTEC/Industry Conference, NAVTRAEQUIPCEN IH-294, Naval Training Equipment Center, Orlando, Florida, November 15-17, 1977.

requirements are relatively easily met. Because visual display correspondence is not required, the reproduction at mid-range to high frequencies is not critical.

The second category includes somewhat larger amplitude motions which are used in a closed loop control sense, and whose correspondence with the visual scene must be sensibly exact (i.e., no detectable discrepancies). The linear motions are still modest — the angular motions are probably less than  $\pm 5$  deg. The engineering fidelity requirements are relatively high but need not extend to large travel. Typical tasks include attitude regulation in light turbulence, perhaps even hover if the visual scene display exhibits negligible delay and the simulated vehicle is well damped. Fidelity at this level is adequate for most regulatory tasks but not for maneuvers.

The third category, besides requiring close correspondence between the visual scene and the motions, also requires large linear travel of the motion base. These motions are necessary to replicate faithfully sensations in discrete maneuvers and are used therein while acquiring skill or as a "background" for monitoring the response to a precognitive maneuver. They are also used as triggering stimuli (e.g., engine failure). This category of fidelity has only been approached in certain research simulators, and typically only for a restricted class of maneuvers. Even so, reproduction of the motion environment at this level is required if the pilot trainee is to progress through all levels in the Successive Organization of Perception for psychomotor skill acquisition in maneuvers.

Meeting the accuracy criteria for the third category of motions is impractical, except in flight, and extremely difficult even for the second category. It is therefore apparent that any practical simulator will compromise these criteria, probably to a substantial degree in the military context of large accelerations and high psychomotor skill requirements.

The methodology outlined herein can identify the differences in pilot task adaptations which will result, presuming that training is continued until a stable, high proficiency performance level is reached in the

simulator. The model is based upon data taken for well trained pilot subjects performing in continuous control tasks. It is somewhat less suitable for predicting adaptations required for the performance of discrete maneuvers; although, even here, the same modeling principles can be applied for analysis — only the data base is deficient.

However, learning dynamics, as influenced by typical simulator motion distortions, are not predicted by the analysis technique. Additional research is required in this area to establish an appropriate empirical data base. The objectives of such research would be to quantify the proficiency level attained versus simulator time as a function of:

- Visual scene delay
- Motion distortion (various descriptors)
- Pilot background
- Flight Task (including controlled element dynamics).

The resulting data base would allow quantification of training effectiveness of a particular simulator by identifying the point of diminishing returns — that point beyond which further exposure is counterproductive or not cost effective for the novice pilot. Such quantification of training effectiveness would be fully compatible with the experimental approaches demonstrated by both Holman<sup>109</sup> and Bickley<sup>110</sup>.

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<sup>109</sup> Holman, Garvin L.: "Suitability-for-Training Evaluation of the CH-47 Flight Simulator," Proceedings of the 11th NTEC/Industry Conference, NAVTRAEQUIPCEN IH-306, Naval Training Equipment Center, Orlando, Florida, November 14-16, 1978.

<sup>110</sup> Bickley, William R., 1980, op cit.

A suggested task for such a research program is that of hovering a helicopter over a spot in moderate turbulence. To build a simulator capable of emulating this task is, in itself, a significant challenge to the state of the art; although the difficulties in replicating the motion are not considered to be insurmountable.

### Visual Perception

The purpose of this section is to develop and to quantify the needed rationale for establishing training simulator visual fidelity requirements. The analytical technique is unique and involves the dynamic modeling of: (a) the training objective (including the pilot's control activities); (b) the perceptual mechanisms of the pilot as affected by motion and visibility limitations; and (c) the resulting apparent geometric forms, locations, angular sizes, and angular velocities relative to perceptual thresholds of information elements within the visual field which provide guidance and control cues to the pilot. These are combined in the identification of those areas of the field of view which are essential for the perception of the cues for guiding and controlling the aircraft to accomplish the training objective. What results is a synthesis of the disciplines of perception, guidance, and control based on external visual spatial and temporal cues. It then becomes possible to assess the fidelity of visual simulation in terms of the distortion, delay, suppression, omission, and/or occlusion of essential cues for a particular training objective.

Summary of Resources. Comprehensive expositions of the bases for understanding human visual perception of spatial and temporal surroundings

were presented by Gibson<sup>111</sup> in narrative form with propositions, axioms, and geometrical graphics which can be tested experimentally. Apparently motivated in part by a concurrent (circa 1950) survey of the status of research in visual perception by Graham<sup>112</sup>, Gilinsky<sup>113</sup> developed and validated a quantitative formulation of visual size and distance perception. Gordon discussed human space perception mathematically in the context of the environmental geometry around a moving eye<sup>114</sup> and set forth the perceptual basis of vehicular guidance<sup>115</sup> in the vicinity of the ground plane. Roscoe<sup>116</sup> has more recently addressed size perception as a function of visual accommodation and found that, in general, eyes focus only well enough for the required discrimination.

The development of visual aids for conventional commercial aircraft approach guidance motivated Calvert (also circa 1950) to extend the theory of visual judgments of motion<sup>117</sup>. Further insight for quantifying flight guidance and control by visual cues has been supplied by Havron<sup>118</sup>,

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- 111 Gibson, J. J., The Perception of the Visual World, Houghton Mifflin, Boston, 1950, Chapters 6 and 7.
  - 112 Graham, C., "Visual Perception," In A Handbook of Experimental Psychology, (S. S. Stevens, Ed.), John Wiley, New York, 1951, pp. 868-920.
  - 113 Gilinsky, "Perceived Size and Distance in Visual Space, 1951, op cit.  
Gilinsky, "The Effect of Attitude Upon the Perception of Size, 1955, op cit.
  - 114 Gordon, D. A., "Static and Dynamic Visual Fields in Human Space Perception," Journal of the Optical Society of America, 55, 1965, pp. 1296-1303.
  - 115 Gordon, "Perceptual Basis of Vehicular Guidance," 1966, op cit.
  - 116 Roscoe, 1979, op cit.
  - 117 Calvert, 1957, op cit.
  - 118 Havron, 1962, op cit.

Naish<sup>119</sup>, and Grünwald and Merhav<sup>120</sup>. These visual cues include, among others, apparent motion of single points and apparent size, orientation, and motion of groups of points which may be fixed in the external panorama, but which appear framed by the windshield boundary; perspective distortions of known geometrical shapes on the ground; perceived rates of change of lineal and areal dimensions of individual objects and their differences from the corresponding rates of change of their apparent background; and perceived changes in uniform ground textures.

### Motion Perspective

The apparent motion of single points which are fixed in inertial space gives rise to the "streamers"<sup>121</sup> of point images, and the apparent motion of inertially-fixed point sets gives rise to the phenomenon of "motion perspective,"<sup>122</sup> created by the streamers of the point set<sup>123</sup>.

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<sup>119</sup> Naish, 1971, op cit.

<sup>120</sup> Grünwald and Merhav, 1976, op cit.

<sup>121</sup> If individual fix points in inertial space are continually observed in uni-directional monocular viewing with the line of sight fixed (or continually moving) in a moving frame, the locus of each fix point is perceived as a continuous curve, called the "streamer." Streamers correspond to the traces created by luminous fix points on the plate of a camera with open shutter and with the optical axis oriented in some specified relation to the moving frame. See Alex, Fredric R., Geometric Foundation of Motion Perceptive, Systems Technology, Inc., Working Paper No. 170-3, January 1967.

<sup>122</sup> When observing in uni-directional monocular viewing a point set on a ground plane fixed in inertial space, a set of correlated streamers is generated which constitute the "expansion pattern" of the region defined by the point set. At any instant this expansion pattern is seen to emanate from an individual motionless "focus of expansion" located at the intersection of the instantaneous velocity vector of the moving frame with the ground plane of the inertial space. The expansion pattern of the streamer set (in relation to the motionless point) is perceived as the "motion perspective" of the subspace spanned by the observed point set. See Ibid.

<sup>123</sup> Ibid.

Apparent size and apparent range of objects in the visual field can be related to true range with the aid of a characteristic measure of perceived range known as the apparent distance of vanishing points from the principles of visual perspective<sup>124</sup>.

Perspective distortions of known geometrical shapes on the ground (or between the observer and the apparent background) can be related to changes in the perceived orientation of groups of points which may be fixed in the external panorama. In turn changes in the perceived orientation of groups of fixed points can be related to changes in the observer's position relative to the object defined by the observed point set.

Perceived rates of change of lineal and areal dimensions of individual objects can be related to the observer's velocity and acceleration relative to the object defined by the observed point set. Whether the perceived rates of change are judged to be caused primarily by the observer's motion or by the object's motion will depend in part on differences in perceived rates of change of the object's motion from the corresponding rates of change of the apparent background.

Finally perceived gradients in uniform ground textures give the observer a continuous impression of distance; and perceived changes in uniform ground textures can be related to changes in slant range, height, and the relative bearing of the observer's line of sight. It then follows that perceived rates of change in uniform ground texture can be related to

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<sup>124</sup> Perceived size,  $S_p$ , and perceived range,  $R_p$ , are related to objective true size,  $S_o$ , and true range,  $R$ , respectively by:

$$\frac{S_p}{S_o} = \frac{R_p}{R} = \frac{1}{1 + R/A}$$

where  $A$  is the apparent distance of vanishing points from the principles of visual perspective (i.e., the apparent distance of objects at an optically infinite distance from the observer.) See Gilinsky, "The Effect of Attitude Upon the Perception of Size," 1955, op cit.



closure rate, vertical velocity, and relative angular velocity of the line of sight, respectively.

Those portions of the theory of visual judgments of motion which concern the acquisition of position, velocity, and acceleration information in both orientation and translation will be applicable to the present study; furthermore, our interest in the essential cues within the field of view will necessarily focus on the training objectives in low altitude operations, including navigation, autorotation, landing, and nap-of-earth and hovering flight where the apparent relative size of the visual elements is great but where the relative velocity between aircraft and landing pad may sometimes be so low as to inhibit the perception of "streamers" which otherwise play a more significant role in conventional visual flight guidance at low altitudes. Consequently for the present study we shall borrow from the theory of visual perception chiefly those essential geometrical constructs and relationships of static perspective which describe relative orientation and position between aircraft and visual elements, some of which are summarized in Tables 7 and 8. Where the relative velocity between aircraft and visual elements is sufficiently great, we shall incorporate those essential geometrical constructs of motion perspective in Table 9 which are vested in the theory of streamers.

Streamers offer the observer the means to discern the point toward which a vehicle is moving (aiming point) from a two-dimensional abstraction of the outside world as projected on the retina. The probable basis for the perception of visual directional information is the expansion pattern of the panorama about the "fixed point" toward which the aircraft is moving. In the parafoveal streamer theory<sup>125</sup> directional information is obtained by the observer, in motion, by making use of the objects in the field of view which appear to move along paths radiating from the fixed point called the "focus of expansion" in the perspective. The vectors tangent to these paths are the "streamers," and the pattern formed

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<sup>125</sup> Gordon, "Perceptual Basis of Vehicular Guidance," 1966, op cit.  
Calvert, 1957, op cit.

TABLE 7. VISUAL FIELD INFORMATION REQUIREMENTS: ORIENTATION


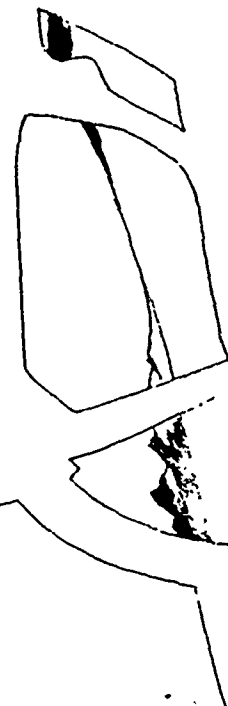

ESSENTIAL FEEDBACK	INNER LOOP PRIMARY CONTROL RESPONSE				RATIONALE FOR REQUIREMENT	TYPICAL EXAMPLES OF VISUAL ELEMENTS
	TRANSFER FUNCTION	INITIATED CLOSURE OF OTHER LOOPS	APPROPRIATE CLOSED LOOP REDUNDANT RATIO	REDUNDANT GENERIC FORM		
Hover or Very Low Speed Flight						
Pitch Attitude	$\frac{\theta}{\delta_c}$	$\begin{matrix} \phi \rightarrow \delta_a \\ \psi \rightarrow \delta_r \end{matrix}$	$\frac{N_{\delta_c}^p \phi + N_{\delta_a}^p \delta_r}{N_{\delta_c}^p \delta_r}$	$\frac{A_0 \left( \frac{1}{T_{\theta 1}} \right)}{(\zeta_p \omega_{sp}) \left( \frac{1}{T_{sp2}} \right)}$	Governs longitudinal acceleration Phugoid unstable $\phi \rightarrow \delta_c$ should damp phugoid without hindrance of low pitch damping Also safety monitor for attitude SAS	
Roll Attitude	$\frac{\phi}{\delta_a}$	$\begin{matrix} \phi \rightarrow \delta_c \\ \psi \rightarrow \delta_r \end{matrix}$	$\frac{N_{\delta_a}^p \phi + N_{\delta_c}^p \delta_r}{N_{\delta_a}^p \delta_r}$	$\frac{A_\phi \left( \frac{1}{T_{\phi 1}} \right)}{(\zeta_{pL} \omega_{pL}) \left( \frac{1}{T_{pL}} \right)}$	Governs lateral acceleration Lateral phugoid unstable $\phi \rightarrow \delta_a$ should damp lateral phugoid without hindrance of low roll damping Also safety monitor for attitude SAS	
Yaw or Heading	$\frac{\psi}{\delta_r}$	$\begin{matrix} \phi \rightarrow \delta_a \\ \psi \rightarrow \delta_c \end{matrix}$	$\frac{N_{\delta_r}^p \phi + N_{\delta_c}^p \delta_a}{N_{\delta_r}^p \delta_a}$	$\frac{A_\psi}{(0) \left( \frac{1}{T_{yd}} \right)}$	Vehicle indifferent to heading $\psi \rightarrow \delta_r$ required for direct regulation of yaw or heading, because of inadequate sideslip stiffness	

TABLE 8a.

## VISUAL FIELD INFORMATION REQUIREMENTS: POSITION

OUTER LOOP PRIMARY CONTROL RESPONSE					
ESSENTIAL FEEDBACK	TRANSFER FUNCTION	IMPLIED CLOSURE OF OTHER LOOPS	APPROPRIATE CLOSED LOOP NUMERATOR RATIO	PREDOMINANT GENERIC FORM for $Y_c$	RATIONALE FOR $F_c$
Longitudinal Position Including Range-to-go	$\frac{x}{\delta_{vx}}$	$\begin{array}{l} \theta \rightarrow \delta_c \\ z \rightarrow \delta_T \\ \varphi \rightarrow \delta_a \\ \psi \rightarrow \delta_r \end{array}$	$\frac{N_{\delta_{vx}}^x \theta z : \varphi \psi}{N_{\delta_c \delta_T \delta_a \delta_r}^x}$	$\frac{X_{\delta_{vx}}}{(0) \left( \frac{1}{T_{\theta 1}} \right) SD} - X_{\delta_{vx}} \leq g$	Necessary for approach guidance, especially at low speeds, in hovering, and landing
	$\frac{x}{\delta_c}$	$\begin{array}{l} \theta \rightarrow \delta_c \\ z \rightarrow \delta_T \\ \varphi \rightarrow \delta_a \\ \psi \rightarrow \delta_r \end{array}$	$\frac{N_{\delta_{vx}}^x z : \varphi \psi}{N_{\delta_c \delta_T \delta_a \delta_r}^x}$	$\frac{-K}{(0) \left( \frac{1}{T_{\theta 1}} \right) SD}$	
Lateral Position	$\frac{y}{\delta_{vy}}$	$\begin{array}{l} \varphi \rightarrow \delta_a \\ \psi \rightarrow \delta_r \\ \theta \rightarrow \delta_c \\ z \rightarrow \delta_T \end{array}$	$\frac{N_{\delta_{vy}}^y \varphi \psi : \theta z}{N_{\delta_a \delta_r \delta_c \delta_T}^y}$	$\frac{Y_{\delta_{vy}}}{(0) \left( \frac{1}{T_{\varphi 1}} \right) LD}$	Necessary for approach, hovering and landing line-up guidance
	$\frac{y}{\varphi_c}$	$\begin{array}{l} \varphi \rightarrow \delta_a \\ \text{or } \delta_{aero} \rightarrow \delta_r \\ \psi \rightarrow \delta_r \\ \theta \rightarrow \delta_c \\ z \rightarrow \delta_T \end{array}$	$\frac{N_{\delta_{vy}}^y \delta_a \text{ or } \varphi : \theta z}{N_{\delta_a \delta_r \delta_c \delta_T}^y}$	$\begin{array}{l} \text{where } \delta_{aero} \text{ is regulated} \\ g \cos \gamma_o / (0)^2 \\ \text{where } \psi \text{ is regulated} \\ g \cos \gamma_o / (1/T_{\varphi 1}) (0) \\ LD \end{array}$	
Normal or Vertical Position Including Altitude-to-go	$\frac{z}{\delta_T}$	$\begin{array}{l} \theta \rightarrow \delta_c \\ x \rightarrow \delta_{vx} \\ \varphi \rightarrow \delta_a \\ \psi \rightarrow \delta_r \end{array}$	$\frac{N_{\delta_T}^z \theta x : \varphi \psi}{N_{\delta_c \delta_{vx} \delta_a \delta_r}^z}$	$\frac{Z_{\delta_T}}{(0) \left( \frac{1}{T_{\theta 2}} \right) ND}$	Necessary for approach, hovering and landing guidance in a vertical plane

Refer to Table 8b for typical examples of visual elements

TABLE 8b. EXAMPLES OF VISUAL POSITION CUES PROVIDED TO THE APPROACHING PILOT  
BY THE GEOMETRY OR DELINEATION OF VISUAL ELEMENTS

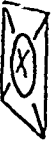
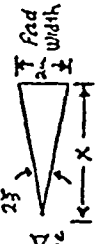

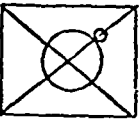




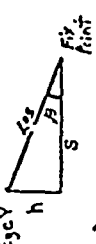

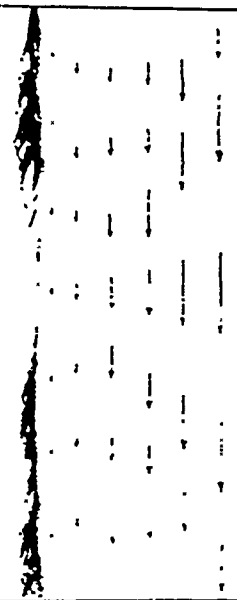
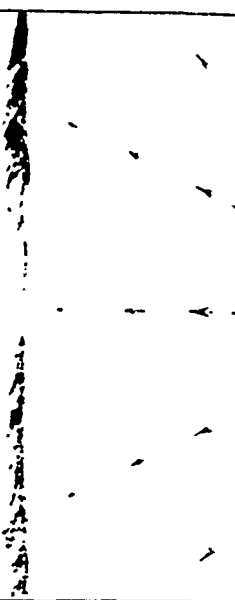
COORDINATE OF POSITION	RATIONALE FOR DELINEATION	CUE PROVIDED BY DELINEATION	TYPICAL VIEW OF DELINEATION	PREFERRED VIEW OF DELINEATION FOR HOVERING	APPARENT SENSITIVITY OF DELINEATION GEOMETRY
Longitudinal Position in Approach	Necessary for approach guidance, especially at low speeds	Apparent size of pad	 See also sketch at bottom of column for close-up	See sketch below	 $\frac{\partial \xi}{\partial (\frac{x}{h})} = -\sin^2 \xi$ becomes greater as $\xi \rightarrow \pi/2$
Longitudinal or Lateral Position in Hovering	Necessary for approach, hovering, and landing line-up guidance	Apparent differential in depression angle of pad outline relative to tree line, terrain, or horizon, if visible	 pad outline	 (Hovering PPI is a candidate for a visual landing aid)	 $\frac{\partial \theta}{\partial (\frac{x}{h})} = \sin^2 \beta$ becomes greater as $\beta \rightarrow \pi/2$
Lateral Position in Approach	Necessary for line-up guidance	Apparent inclination of diagonal representing center line with respect to horizontal diagonal; also asymmetry of rectilinear outline.	 center line	See sketch above	 center line $\frac{\partial \psi}{\partial (\frac{x}{h})} = -\cot \gamma \sin^2 \psi$ $\frac{\partial \psi}{\partial (\frac{x}{h})}$ becomes greater as $\psi \rightarrow \pi/2$ , i.e., when aligned. $s$ = range-to-go, $y$ = lateral offset from centerline extension
Normal or Vertical Position	Necessary for approach, hovering and landing guidance in a vertical plane	Glide slope deviation would be provided by VTA during approach Altitude itself is provided in terms of tree line or terrain line, if nearby. Apparent size of pad outline or apparent depression angle of pad outline also provides height cue			 $\frac{\partial \theta}{\partial (\frac{x}{h})} = \cos^2 \beta$ becomes greater as $\beta \rightarrow 0$

TABLE 9. VISUAL FIELD INFORMATION REQUIREMENTS: TRANSLATIONAL VELOCITY

ESSENTIAL FIELD	OUTER LOOP PRIMARY CONTROL RESPONSE				RATIONALE FOR INFORMATION	TYPICAL EXAMPLES OF VISUAL ELEMENTS
	TRANSFER FUNCTION	IMPLIED CLOSURE OF OTHER LOOPS	APPROPRIATE CLOSED LOOP INDEPENDENT RATIO	PREDOMINANT GENERIC FORM for $Y_2$		
Surge (or Longitudinal) Velocity	$\frac{z}{b_{vx}}$ $z = u + u_0 \theta$	$\theta \rightarrow b_e$ $z \rightarrow b_r$ $\phi \rightarrow b_a$ $\psi \rightarrow b_r$	$\frac{N_{\delta vx}^z \theta z : \phi \psi}{N_{\delta vx}^z \delta_e b_r : \delta_a b_r}$ $\frac{N_{\delta vx}^z \theta z : \phi \psi}{N_{\delta vx}^z \delta_e b_r : \delta_a b_r}$	$\frac{x_{\delta vx}}{\left(\frac{1}{T_{\delta vx}}\right)}_{SD}$ $-x_{\delta vx} \leq \epsilon$	Necessary for guidance and for damping longitudinal position regulation	
	$\frac{z}{b_c}$	$\theta \rightarrow b_e$ $z \rightarrow b_r$ $\phi \rightarrow b_a$ $\psi \rightarrow b_r$	$\frac{N_{\delta vx}^z \theta z : \phi \psi}{N_{\delta vx}^z \delta_e b_r : \delta_a b_r}$ $\frac{N_{\delta vx}^z \theta z : \phi \psi}{N_{\delta vx}^z \delta_e b_r : \delta_a b_r}$	$\frac{x_{\delta vx}}{\left(\frac{1}{T_{\delta vx}}\right)}_{SD}$		
Sway (or Lateral) Velocity	$\frac{z}{b_{vy}}$	$\theta \rightarrow b_e$ $z \rightarrow b_r$ $\phi \rightarrow b_a$ $\psi \rightarrow b_r$	$\frac{N_{\delta vy}^z \theta z : \phi \psi}{N_{\delta vy}^z \delta_e b_r : \delta_a b_r}$ $\frac{N_{\delta vy}^z \theta z : \phi \psi}{N_{\delta vy}^z \delta_e b_r : \delta_a b_r}$	$\frac{x_{\delta vy}}{\left(\frac{1}{T_{\delta vy}}\right)}_{LD}$	Necessary for guidance and for damping lateral position regulation	
	$\frac{z}{\phi_c}$	$\theta \rightarrow b_e$ $z \rightarrow b_r$ $\phi \rightarrow b_a$ $\psi \rightarrow b_r$	$\frac{N_{\delta vy}^z \theta z : \phi \psi}{N_{\delta vy}^z \delta_e b_r : \delta_a b_r}$ $\frac{N_{\delta vy}^z \theta z : \phi \psi}{N_{\delta vy}^z \delta_e b_r : \delta_a b_r}$	where $\delta_{macro}$ is regulated $\delta \cos \gamma_{\delta}(0)$ where $\gamma$ is regulated $\delta \cos \gamma_{\delta}(1/T_{\delta vx})$ $LD$		
Heave (or Normal) Velocity	$\frac{z}{b_r}$	$\theta \rightarrow b_e$ $z \rightarrow b_r$ $\phi \rightarrow b_a$ $\psi \rightarrow b_r$	$\frac{N_{\delta r}^z \theta z : \phi \psi}{N_{\delta r}^z \delta_e b_r : \delta_a b_r}$ $\frac{N_{\delta r}^z \theta z : \phi \psi}{N_{\delta r}^z \delta_e b_r : \delta_a b_r}$	$\frac{z b_r}{\left(\frac{1}{T_{\delta r}}\right)}_{ID}$	Necessary for guidance and for damping vertical position regulation	
	$\frac{z}{d} = \frac{v - u_0 \theta}{d}$	$\theta \rightarrow b_e$ $z \rightarrow b_r$ $\phi \rightarrow b_a$ $\psi \rightarrow b_r$	$\frac{N_{\delta r}^z \theta z : \phi \psi}{N_{\delta r}^z \delta_e b_r : \delta_a b_r}$ $\frac{N_{\delta r}^z \theta z : \phi \psi}{N_{\delta r}^z \delta_e b_r : \delta_a b_r}$			
Vertical Velocity	$\dot{h} = v_0 \sin \theta_0 \theta - v \cos \theta_0 + u \sin \theta_0 + u_0 \cos \theta_0 \theta$					

by them is the point toward which the observer is moving. Sometimes this point can be observed directly as when the observer's speed is high, weather is clear, and objects are close. Otherwise the location of the point must be inferred by extrapolation of the streamer pattern characteristics of various types of objects and ground texture.

Ringland, et al.,<sup>126</sup> presents an analysis showing how the interpretation of motion perspective geometry will enable the observer to anticipate changes in the future course of his motion. When present and recognized, these essential visual elements from motion perspective, in turn, will enable an observant controller to provide first- and second-order visual lead compensation<sup>127</sup> of his controlled element without the customary intensive psychomotor workload which accompanies visual anticipation of low frequency motions.

### Pattern Recognition

Perfect recognition by the pilot of the visual elements which are necessary for guidance and control of the aircraft in low altitude operations is an idealization of reality even though in most low altitude tasks the experienced pilot must recognize changes in very familiar memorized geometric patterns. Memorizing and recognizing a pattern involve cognitive activities which can be considered analogous to memorizing and repeating a sequence of psychomotor activities. Table 10 presents the summary of a sequential pattern perception and recognition theory from

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126 Ringland, Robert F., Warren F. Clement, and Henry R. Jex, Factors in Determining Visual and Motion Fidelity Requirements for Training Simulators, Systems Technology, Inc., Working Paper No. 1162-4, December 1980, Revised March 1981.

127 Second order lead compensation here is akin to the adoption of pursuit behavior measured in: Allen, R. Wade, and Duane McRuer, The Man/Machine Control Interface -- Pursuit Control, Systems Technology, Inc., Paper No. 243, April 1979.

TABLE 10. SUMMARY OF A SEQUENTIAL PATTERN PERCEPTION THEORY

SUMMARY OF A SEQUENTIAL PATTERN PERCEPTION CENTERED AND RECOGNITION THEORY (From Noton <sup>128</sup> )	REMARKS AND CONNECTIONS WITH PERCEPTUAL CENTERED AND OTHER MODELS
1) Memorizing a pattern is the process of constructing an internal representation of the pattern in memory, in the form of a sequential feature network, a closed network of memory traces recording the features of the pattern and the attention shifts required to pass from feature to feature across the visual field.	1) Closed cyclic nature of feature network.
2) Recognizing a pattern is the process of finding in memory a feature network which matches the pattern, the matching being carried out sequentially feature by feature.	2) Closed-loop process of recognition; "matching" proceeds at the <u>compensatory level</u> in the most unfamiliar situations.
3) The attention shifts from feature to feature may take the form of saccadic eye movements or of internal attention shifts, according to the angular displacement involved.	3) Consistent with Sanders' findings <sup>129</sup> , <u>internal</u> attention shifts proceed at neural speeds.
4) During recognition the matching process is guided by the feature network, which directs attention from feature to feature of the pattern.	4) "Matching" is aided by short-term memory which is consistent with Sperling's findings <sup>130</sup> . Peripheral vision may also guide the matching process at the <u>pursuit-level</u> in more familiar situations.
5) The directed nature of the matching process (note in 4) is the key to the recognition of patterns in the presence of noise and clutter. The feature network directs attention to the features of the pattern, while avoiding the noise and clutter.	5) Consistent with Mackworth's findings that visual noise causes tunnel vision <sup>131</sup> .
6) Memorizing and recognizing a pattern are seen to be closely analogous to memorizing and repeating a conventional sequence of behavior, each being an alternating sequence of sensory and motor activities.	6) Consistent with successive organization of perception (SOP) theory <sup>132</sup> .
7) This habit produces the scan-path, a habitually preferred path followed from feature to feature through the feature network and, correspondingly, across the visual field. This path differs from person to person and from pattern to pattern, but is fixed and characteristic for a given person viewing a given pattern.	7) Uncharacterized by great determinism.
8) Under conditions in which attention shifts must take the form of eye movements, the development of the scan-path during memorization of a pattern has been experimentally demonstrated. Its use in subsequent recognition awaits confirmation.	8) Contrast these findings with the apparent lack of determinism in instrument scanning under IFR reported by Pitts, et al.; Weir and Klein; Clement, et al., and Clement, et al., <sup>133</sup> and their antecedents.

128 Noton, 1970, op cit.

129 Sanders, A. F., "Some Aspects of the Selective Process in the Functional Visual Field," *Ergonomics*, 13, 1970, pp. 101-117.

130 Sperling, G., "Successive Approximations to a Model for Short Term Memory," *Acta Psychologica*, 13, 1970.

131 Mackworth, N. H., "Visual Noise Causes Tunnel Vision," *Psychoneurological Sciences*, 3, 1965, pp. 67 and 68.

132 McRuer and Krendel, 1974, op cit.

133 Pitts, Jones, and Milton, 1950, op cit.

Weir and Klein, 1970, op cit.

Clement, W. F., et al., Application of Manual Control Display Theory to the Development of Flight Director Systems for STOL Aircraft: Part II: Multi-Axis Sampling, Pilot Workload, and Display Integration, Systems Technology, Inc., Technical Report No. 1011-2, 1974.

Clement, W. F., et al., A Reexamination Of Pilot Eye Movement Data, Systems Technology, Inc., Technical Memorandum No. 163-A, Rev. 25 February 1967.

Noton<sup>134</sup> together with some remarks and connections with the SOP theory and other findings which have been found to be useful in characterizing visual perception and cognitive activities. In terms of the successive organization of perception theory<sup>135</sup> and the sequential theory of pattern perception in Noton<sup>136</sup>, the experienced pilot is probably always operating at least at the pursuit level of pattern perception. At the pursuit level of pattern perception, it may be reasonable to assume that recognition is conditioned only upon detection with fairly high probability, say 0.95, and insignificant additional time delay over that already accounted for in the effective perceptual-motor delay,  $\tau_e$ , of the crossover model for the compensatory level of control, unless head movements are required to scan the functional visual field as defined, for example, by Sanders' selective process<sup>137</sup>.

In contradistinction, the student pilot may not yet have memorized all of the changing geometric patterns in the visual elements which are necessary for guidance and control of the aircraft in low altitude operations. Thus the student pilot may be operating at the compensatory level of pattern perception as well as the compensatory level of control. At the compensatory level of pattern perception, recognition may be conditioned upon detection with a lower probability than 0.95 and additional time delay over that already accounted for in the effective perceptual-motor delay,  $\tau_e$ , of experienced pilots. Experiments to test this hypothesis with a student pilot population have yet to be conducted.

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134 Noton, D., "A Theory of Visual Pattern Perception," IEEE Transactions, SSC-6, 1970, pp. 349-357.

135 McRuer and Krendel, 1974, op cit.

136 Noton, 1970, op cit.

137 Sanders, 1970, op cit.



Sanders has shown in a decade of visual research at the TNO in the Netherlands<sup>138</sup> that a "scanning controller" function exists which directs the motions of the eye and head to points of interest in the visual field. For our purposes, "points of interest" in the functional visual field would correspond to the locations of visual elements and geometric patterns which are necessary for guidance and control of the aircraft. We have called these points of interest essential "cues" for brevity. For cues at angles from the foveal axis of less than about 20 deg, the eye need not, but may, be moved; for angles between 20 and 60 deg only the eye is moved in one dominant saccade at a slew rate on the order of 300 deg/sec. For points-of-interest further than 60 deg, the head is moved as well, thus requiring more time to complete the saccade.

Numerous experiments<sup>139</sup>, using eye- and head-point-of-regard instrumentation, have shown that both the eye and head tend to move in a series of very sharp saccades (steps) while changing one's point of regard. The resulting image blur during a saccade is suppressed internally by a feed-forward signal from the eye movement controller, so that perception is briefly lost during each saccade. Thus the net effect on the perception of a cue's form or motion is a short average delay due to scanning

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138 Ibid.

139 Fitts, P. M., R. E. Jones, and J. L. Milton, "Eye Movements of Aircraft Pilots During Instrument-Landing Approaches," Aeronautical Engineering Review, Vol. 9, No. 2, Feb. 1950, pp. 24-29.

Weir, D. H., and R. H. Klein, The Measurement and Analysis of Pilot Scanning and Control Behavior During Simulated Instrumented Approaches, NASA CR-1535, June 1970.

Young, L. R., L. Stark, and C. Kupfer, Physiology of the Visual Control System, NASA CR-238, June 1965.

saccades.<sup>140</sup> Consequently our divided or intermittent attention models for perception<sup>141</sup>, coupled with Gilinsky's models for the perception of size and distance<sup>142</sup> and streamer theory<sup>143</sup>, should be adequate for application in the guidance and control analysis for the present study.

Perception of the changing geometric properties, however, is conditioned upon the perceived photometric properties, such as illuminance, reflectance, and color, which will be altered by environmental attenuation and scattering. At the relatively short visual ranges to the visual element from hovering and near-hovering positions, scattering is the predominant effect at night. Scattering acts to reduce contrast and to desaturate colors<sup>144</sup>. Backscatter from landing lights on the aircraft, intermittent attenuation from precipitation and the possibility of reflected glare from flood lights provide a complex distribution of veiling luminance in the external field of view at night. Scattering and attenuation increase with the density of precipitation (e.g., rain, sea spray, fog) and the range of the observer.

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<sup>140</sup> The details of the intentional movement dynamics of both the head and eye are fairly well known and are quite complex in detail (e.g., Ibid). However, because the saccades are rapid (less than 0.06 sec for eye-only motions), for purposes of analysis and evaluation the effect can be represented by a delay in perception of displayed states. This delay can be lumped with a typical detection delay of about 0.02 sec.

<sup>141</sup> McRuer and Krendel, 1974, op cit.

<sup>142</sup> Gilinsky, "Perceived Size and Distance in Visual Space," 1951, op cit.

Gilinsky, "The Effect of Attitude Upon the Perception of Size," 1955, op cit.

<sup>143</sup> Gordon, 1965, op cit.

<sup>144</sup> Middleton, W. E. Knowles, "Vision Through the Atmosphere," Canada: University of Toronto, 1952.

## Visibility Effects

Luminant source attenuation effects, which predominate in daylight, have been described by the Koschmeider theory<sup>145</sup>. The effects of backscatter and glare at night cause the inherent contrast of a luminant source to attenuate more rapidly than is described by the (exponentially) linear relationship with range identified as Koschmeider's law<sup>146</sup>. The effects of backscatter and glare can, however, be imbedded in a modification of Koschmeider's law by representing the exponent as a truncated power series in range,  $R$ <sup>147</sup>.

Allen and McRuer<sup>148</sup> have coupled the modified Koschmeider theory with the modified Blackwell-Davies contrast thresholds<sup>149</sup> in studies of how the

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<sup>145</sup> Ibid.

<sup>146</sup> Frenk, R. S., D. E. Skaar, and J. A. Tennant, "Driver's Visual Detection," SAE Paper 720142 presented at the SAE Automotive Engineering Congress, Detroit, Michigan, 10-14 January 1972.

<sup>147</sup> The observed luminance contrast  $C_R$ , at range,  $R$ , is given by

$$C_R = C_0 \exp (-\sigma R - \lambda R^2 - \dots)$$

where  $C_0$  = inherent source or target contrast  
 $\sigma$  = Koschmeider's meteorological extinction coefficient  
 $\lambda$  = backscattering coefficient

<sup>148</sup> Allen, R. W., and D. T. McRuer, "The Effect of Adverse Visibility on Driver Steering Performance in an Automobile Simulator," SAE Paper 770239, March 1977.

<sup>149</sup> Davies, E. B., Contrast Thresholds for Air to Ground Vision, RAE Technical Report 65089, April 1965.

Blackwell, H. R., "Contrast Thresholds of the Human Eye," J. of the Optical Society of America, No. 36, 1946, pp. 624-643.

Blackwell, H. R., and D. W. McCready, Jr., "Foveal Detection Thresholds for Various Durations of Target Presentation," Minutes and Proceedings of NAS-NRC Vision Committee, November 1952, ACSIL/53/4405.

visual segment can affect perceptual cues for guidance and control of surface vehicles. The same technical approach has been applied by Clement and Heffley<sup>150</sup> to estimate the minimum effective visual range for guidance and control of VTOL operations at night.

Jewell, et al.,<sup>151</sup> describe a simple method for measuring and comparing, in the closed-loop context involving the human operator, various techniques of obtaining computer-generated images (CGI). The proposed method is independent of the manufacturers' hardware and software specifications and allows different CGIs to be compared in situ on an absolute scale as well as back to back. Furthermore the method also offers a rational means for evaluating hardware and/or software changes to extant CGI systems and to their host computation systems which provide the aircraft mathematical model. For example a carefully designed experiment using the method described in Jewell, et al.,<sup>152</sup> can reveal how the effects of asynchronous data transfer and lead prediction or smoothing compensation in the CGI software affect the performance of the human operator in accomplishing a specific training objective.

The optimal control and estimation methods demonstrated by Wewerinke<sup>153</sup>; Baron, et al.,<sup>154</sup>; and Zacharias and Levison<sup>155</sup> offer a

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- 150 Clement, Warren F., and Robert K. Heffley, Some Effects of Adverse Visibility on Threshold Properties of the Pilot's Perception in VTOL Approaches to Non-Aviation Ships, Systems Technology, Inc., Working Paper No. 1115-3, May 1978.
- 151 Jewell, Wayne F., and Warren F. Clement, A Simple Method for Measuring the Effective Delay in Simulator Digital Computing Systems Involving Manual Control, Systems Technology, Inc., Working Paper No. 1156-4, December 1980.
- 152 Ibid.
- 153 Wewerinke, P. H., Visual Scene Perception Process Involved in the Manual Approach, NLR-TR-78130U, 1978.
- 154 Baron, Lancraft, and Zacharias, 1980, op cit.
- 155 Zacharias, Greg L., and William H. Levison, "A Model-Based Procedure for Determining Visual Cue Requirements," 1981 IMAGE II Conference Proceedings, AFHRL, Scottsdale, Arizona, 10-12 June 1981.

means of calculating the relationships between the geometric pattern details and the quality of state information used by the pilot. Care must be exercised, however, to insure that the "optimal" solutions really do reflect correct or realistic piloting technique and task performance. It may be advisable to simply use such methods to establish likely starting points for pilot-vehicle models which are then studied in order to reveal the fundamental first-principles effects. The concern is that the mathematical complexity usually associated with optimal control and estimation procedures might cloud the insight necessary to identify basic cause-effect relationships. (These same comments also apply to use of optimal control techniques in conjunction with motion fidelity.)

Sensitivity of Visual Cues in Low Altitude Operations. We have already presented in Tables 7, 8, and 9 some examples of key roles for visual cues in low altitude operations. In this topic we shall introduce a measure of sensitivity which affects the pilot's perception of those essential geometric properties of visual elements which provide position information upon which he, in turn, takes action to control. This measure of sensitivity is also summarized in Table 8.

The need for a wide parafoveal — even peripheral — awareness of position and velocity cues is apparent from the appearance of the landing pad in Fig. 31. This is a polar picture plane representation of the forward field of view from the left seat of the XC-142 in a level attitude<sup>156</sup>. The appearance of a circular landing pad is shown as the aircraft proceeds on a constant vertical rate of descent approach at constant horizontal deceleration. Notice that even under visual conditions the tracking of the aiming point<sup>157</sup> with respect to the pad is a pursuit

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156 See Roberts, Edward O., External Visibility Criteria for VTOL Aircraft, AFFDL-TR-67-27, March 1967, for the method of representation.

157 A geometric construction for inferring the approximate location of the moving aiming point is illustrated in Fig. 32. Notice that the aiming point will always pursue the pad from a shallower depression angle, i.e., from "above" the apparent pad, until arrival over the spot for hover.

Polar picture plane representation of forward hemispheric field of view

$$\text{Hover altitude} = \text{pad radius} = 2\tau_a \dot{h}$$

$\dot{h}$  = rate of descent  
 $a_x$  = horizontal deceleration  
 $\tau_a = \dot{h}/a_x$  = normalizing unit of time

Elapsed time interval between successive apparent locations of pad is  $\tau_a$

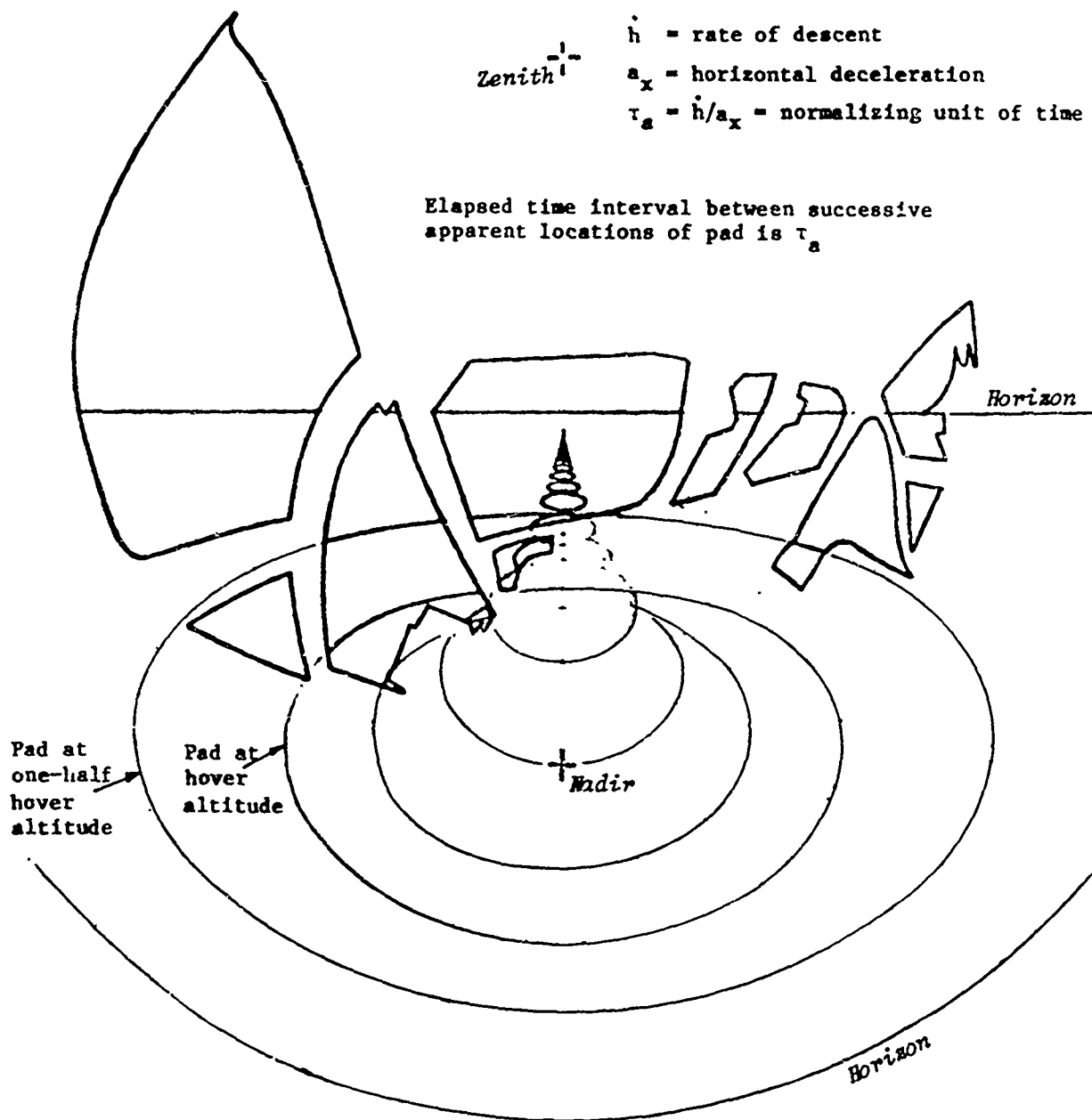


Figure 31. Circular Pad Appearance in Vertical Landing Approach at Constant Rate of Descent and Horizontal Deceleration From Left Seat of XC-142 Cockpit

Zenith  $\downarrow$

To locate aiming point, construct lines EP and E'P tangent to their respective loci of extremities of the pad's major axis EE'. The intersection P is the aiming point from which all apparent motion streamers will originate.

Locus of extremities of the Semimajor axis corresponding with the elliptic apparation of the pad

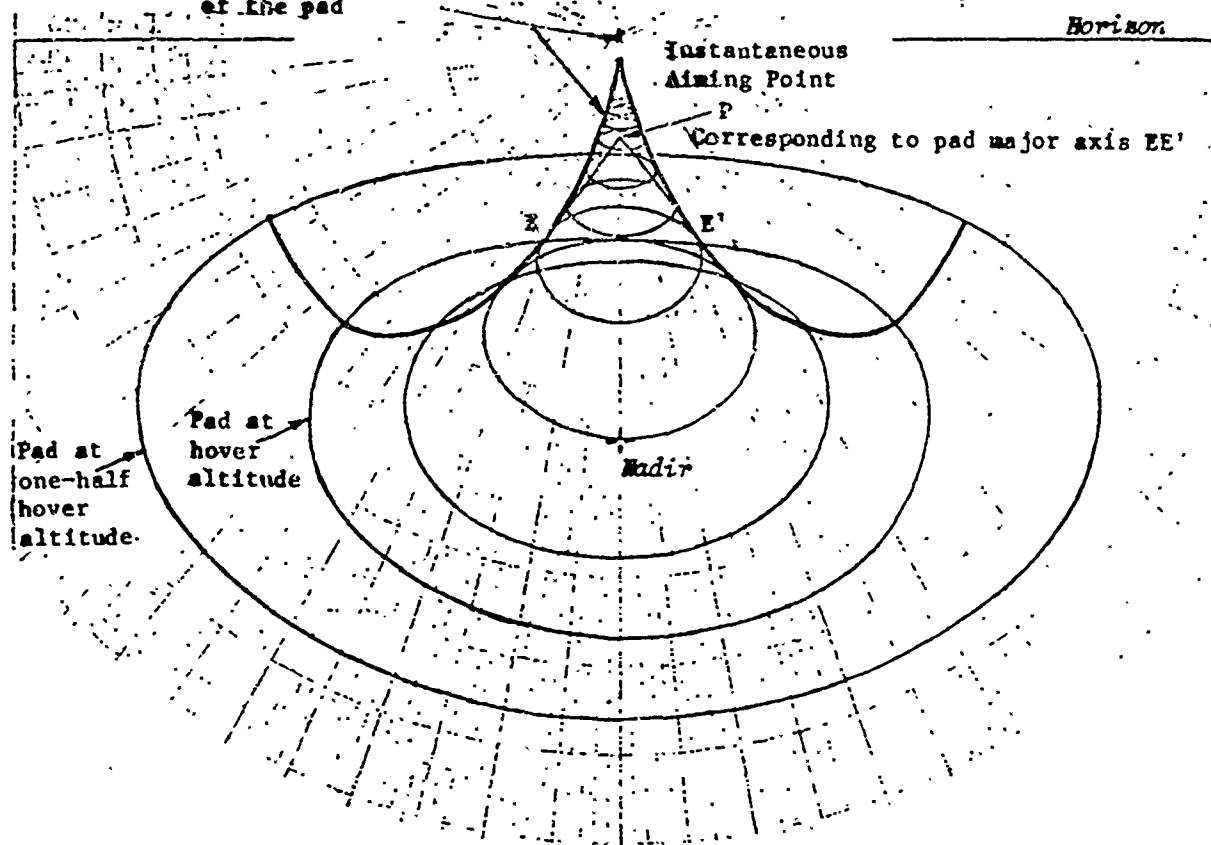


Figure 32. Inference of Aiming Point Location From the Apparent "Motion Streamers" Associated with a Circular Pad in a Vertical Landing Approach at Constant Rate of Descent and Constant Horizontal Deceleration

task until the pad is occulted by the nose. In this aircraft, which has a rather generously depressed field of view, the pad is marginally visible throughout the critical portion of the conversion to hover. This profile is most prone to pad overshoot when a transition from instrument flight rules to visual flight rules is required.

The appearance of a circular landing pad with reduced visual range is shown in Fig. 33 for the same type of approach as in Fig. 31. The maximum slant visual range is assumed equal to 17 pad radii (approximately 700 ft). For example if the rate of descent,  $\dot{h} = 10$  ft/sec, and the horizontal deceleration,  $a_x = 5$  ft/sec<sup>2</sup>, the normalizing unit of time,  $\tau_a = 2$  sec, and the pad radius in Figs. 31, 32, and 33 will be 40 ft. Note that for this case the maximum slant visual range will be 680 ft, which corresponds roughly to Runway Visual Range for ICAO Category III-A. Notice how little time (5 sec) is available after acquiring visual contact with the pad to establish pursuit tracking of the inferred aiming point with respect to the pad before the pad is occulted by the nose. Thereafter inference of the aiming point from motion streamers is hampered by the occultation unless other ground texture besides a partial glimpse of pad outline becomes visible. Yet the pilot must continue to pursue the inferred center of the pad with the inferred aiming point until coincidence is achieved, whence the pure descent can be arrested in hover over the pad.

When the angular regions in the field of interest defined by Sanders' selective process (p. 123 herein) are considered, it is clearer why pilots may experience significant workload in acquiring external visual cues close to the pad. Experimental work reported in Gordon<sup>158</sup>, while applied to automobile driving, confirms that the use of small aperture viewing (without correspondingly improved viewing resolution) is reported to cause increased workload, suggesting that denial of the peripheral cues may lead

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<sup>158</sup> Gordon, 1966, op cit.



Polar picture plane representation of forward hemispheric field of view

Max slant visual range = 17 pad radii  
 Hover altitude = pad radius =  $2\tau_a h$

$\dot{h}$  = rate of descent

$a_x$  = horizontal deceleration

$\tau_a = \dot{h}/a_x$  = normalizing unit of time

Zenith  $\uparrow$

Elapsed time interval between successive  
 apparent locations of pad is  $\tau_a$

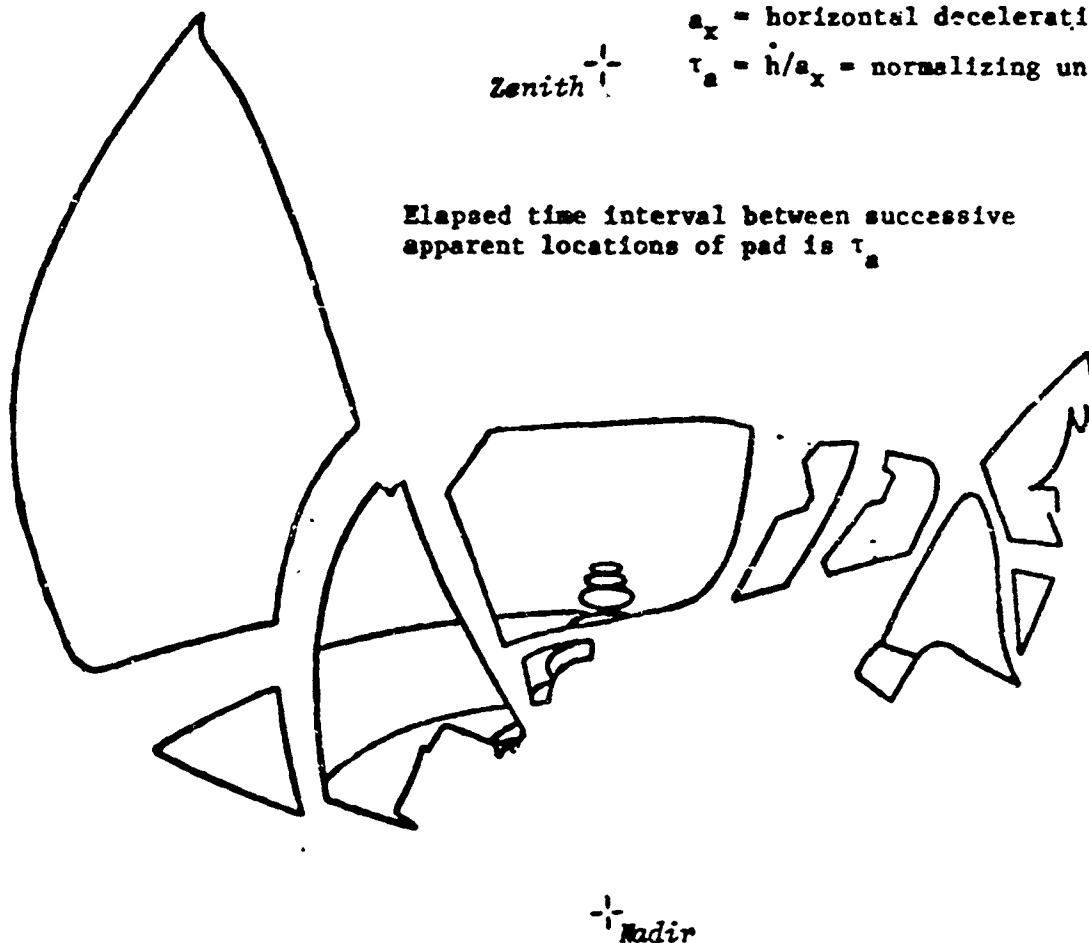


Figure 33. Circular Pad Appearance in Vertical Landing Approach at Constant Rate of Descent and Horizontal Deceleration with Reduced Visual Range From Left Seat of XC-142 Cockpit

to significant degradation in the perceptive structure, a point also addressed by Roscoe<sup>159</sup>.

Figure 34 shows a short runway approach viewed from inside the same aircraft. A constant glide slope angle of 9 deg is maintained. Notice how the depression angle of the runway threshold at a constant 9 deg below the horizon coincides with the fixed aiming point and offers a compensatory cue for maintaining position on the glide slope. Furthermore the perspective angle of the line-up centerline or the asymmetry of the (lighted) runway outline will provide a compensatory lateral displacement cue as shown in the inset at the lower left corner of Fig. 34. The transition to a level of skill higher than compensatory is thus postponed until the flare point is approached or until the minimum go-around decision altitude is reached. The runway appears in the pilot's tunnel field of view throughout most of the approach. This constant-angle profile offers superior potential for compatible instrument-to-visual transitions.

If the maximum slant visual range be limited to 1000 ft (2/3 of the runway length in Fig. 34), the appearance of the runway will be as shown in Fig. 35. Although the (lighted) approach line-up centerline will appear long before the runway threshold outline, perception of the perspective angle of the line-up centerline for the purpose of lateral guidance will be compromised by the absence of an external local horizon. After the threshold appears, its depression angle will be useless as a glide slope position cue unless a collimated artificial horizon is displayed (head-up) in registration with the (invisible) local horizon. Therefore, in addition to its vital role as an attitude reference, a collimated artificial horizon perfectly registered with the local horizon is essential to the abstraction of line-up and glide slope displacement information after transition to visual contact with the ground, if the external local horizon is occluded.

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<sup>159</sup> Roscoe, 1979, op cit.

Polar picture plane representation of forward hemispheric field of view

Flare altitude = 33 ft

Runway length = 1500 ft

Runway width = 100 ft

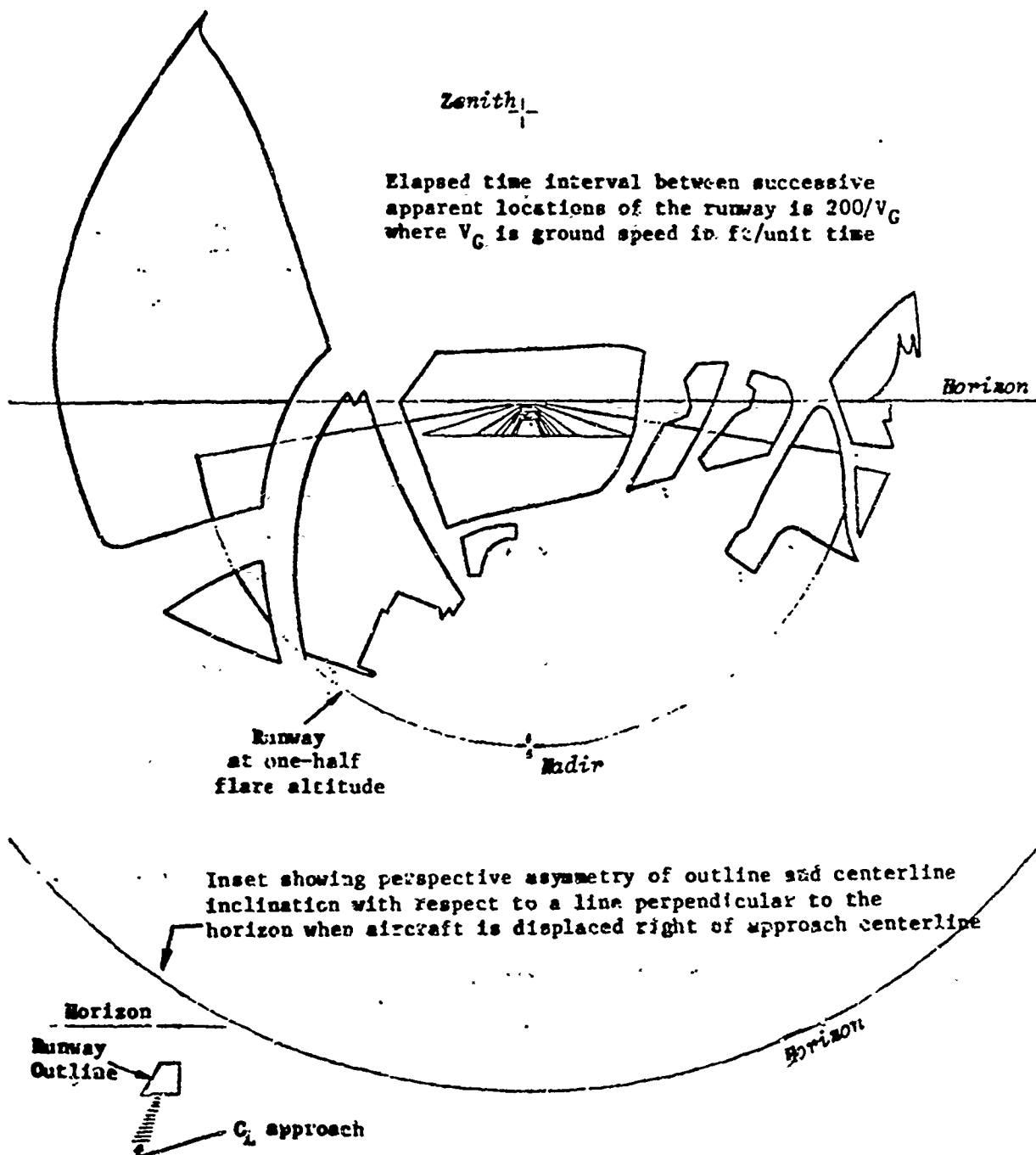
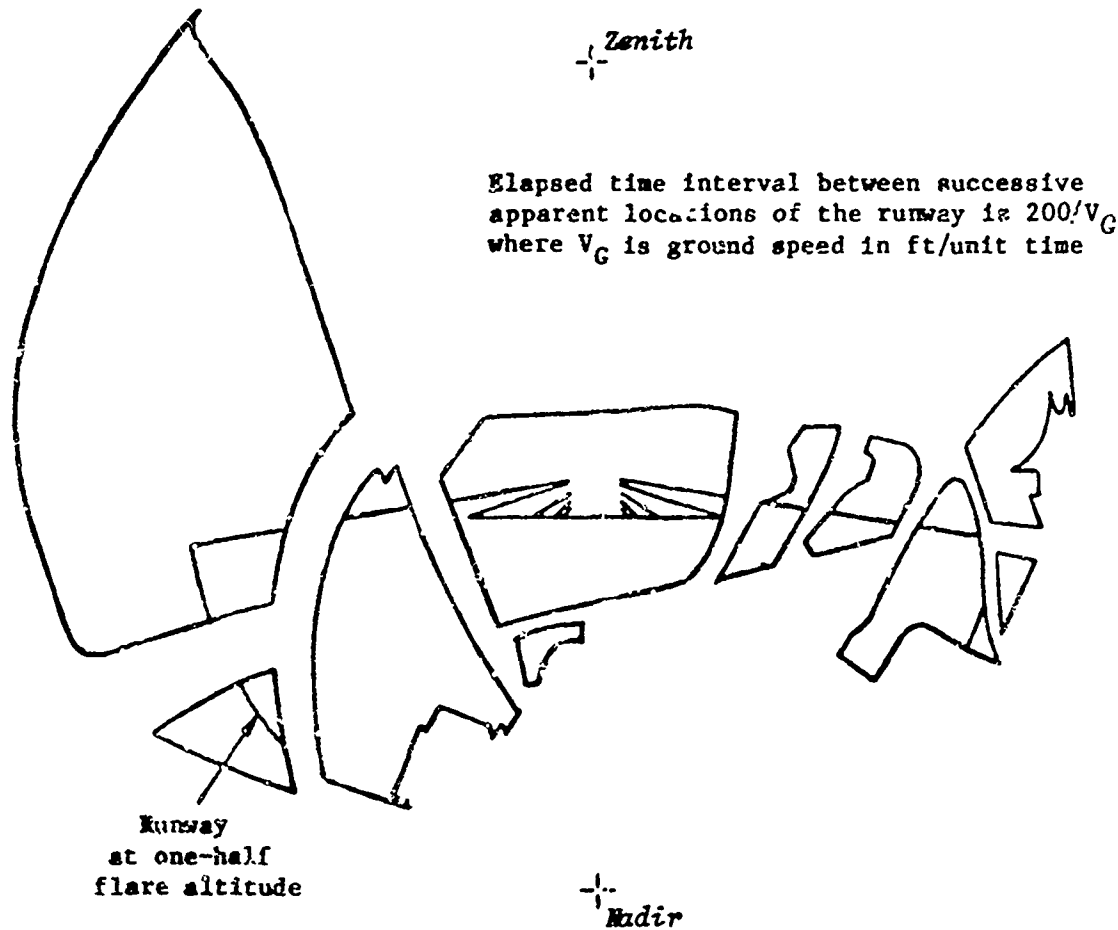


Figure 34. Runway Appearance in a Short Landing Approach at 9 deg Glide Angle and Constant Ground Speed From Left Seat of XC-142 Cockpit

Polar picture plane representation of forward hemispheric field of view

Max slant visual range = 1000 ft  
Flare altitude = 33 ft

Runway length = 1500 ft  
Runway width = 100 ft



Inset showing perspective asymmetry of outline and centerline inclination with respect to a line perpendicular to the horizon when aircraft is displaced right of approach centerline

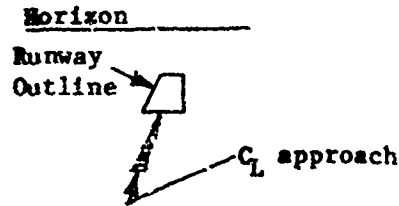


Figure 35. Runway Appearance in a Short Landing Approach at 9 deg Glide Angle and Constant Ground Speed with Reduced Visual Range From Left Seat of XC-142 Cockpit

Considerations for Vertical Displacement Control. Expressions are shown in the extreme right column of Table 8b, for the sensitivity of the line of sight depression angle,  $\beta$ , to changes in ground position,  $x$ , and height,  $h$ . The advantage of the constant path angle approach to the runway or pad is the compensatory guidance and control feature of the runway or pad appearance at constant depression angle. The superior altitude sensitivity of pad depression angle on shallow path angle approaches is evident from the expression for  $\partial\beta/\partial(h/S)$  in Table 8b where the sensitivity decays as the square of the cosine of the depression angle of the line of sight to the pad. The altitude sensitivity is quite acceptable over the range of relatively shallow approach angles.

In contrast, the sensitivity of lateral and longitudinal ground position cues while in hover and near transition to hover is unfortunately best at large depression angles near the nadir. This underscores the need to keep the simulated gradient of scale in ground texture consistent with slant range at large depression angles. Forward field of view at these angles is nearly impossible to provide in aircraft.

Hover position sensitivity perceived by the pilot falls off to about half its maximum value as the line of sight rises to 45 deg depression. This two-fold change in ground position sensitivity while on VFR is most important when teaching a student to transition from a hover position display to a head-up display. We have seen a variety of simulated plan position indicators which present the nadir view of the pad in relation to the aircraft or the aircraft in relation to the pad. While using such an instrument, the pilot has the advantage of maximum longitudinal and lateral displacement sensitivity over the ground, yet when he seeks the transition to visual contact, his line of sight depression angle to the hangar or pad may be much less than 45 deg. On acquiring the hangar or pad visually, the pilot may discover that the displacement sensitivity is less than half that to which he was accustomed on instruments. Thus the pilot is suddenly required to adapt his loop gain to the change in perceived displacement sensitivity. Although a three- or four-fold increase in pilot gain is quite possible, the IFR/VFR transition point is a very unfair place to require it, since the pilot is preoccupied with vehicle trim changes and with the transition to hover in an unforgiving vehicle.

Considerations for Lateral Displacement Control. Consider the pilot's view of the landing pad centerline as seen from a point short of the pad and displaced to the left. Geometrically the situation is as shown in the left portion of Fig. 36, with the pilot's eye view shown on the right. The

- $\gamma$  = Nominal Glide Slope Angle  
 $\nu$  = Approach Line Up Centerline Perspective Angle  
 $y$  = Lateral Displacement  
 $h$  = Altitude  
 $\overline{F_1 F_2}$  = Line Up Centerline

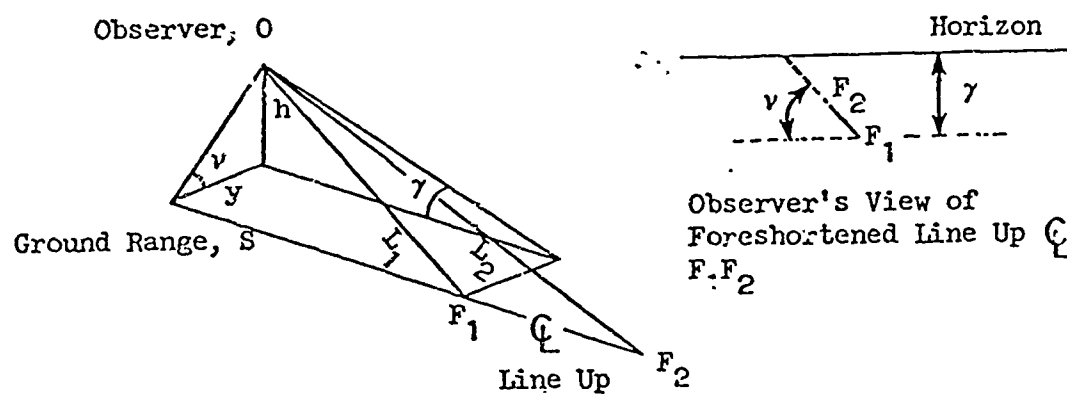


Figure 36. Geometry for Perception of Time-Advanced Lateral Deviation

sensitivity of the perspective angle,  $v$ , to changes in lateral displacement,  $y$  (with the latter normalized by the ground range,  $S$ ), is equivalent to the partial derivative, i.e.,

$$\frac{\partial v}{\partial(y/S)} = -\cot \gamma \sin^2 v$$

This sensitivity is greatest at shallow depression angles (small  $\gamma$ ) when  $v$  is near 90 deg, i.e., when nearest to being lined up with the pad centerline. It falls to half of this value for  $v = 45$  deg and increases rapidly toward zero for decreasing  $v$ . The strong lateral displacement or line-up cue provided by the line-up centerline is also evident in the inset in Figs. 34 and 35.

One way in which the line-up centerline displacement cues can provide for adoption of an advantageous lateral displacement control loop-structure on the part of the pilot is shown by Ringland, et al.,<sup>160</sup>. The perspective angle of the line-up centerline in combination with its time rate of change provides an effective time-advanced lateral deviation<sup>161</sup>. Preview is explicit in this case simply by viewing the perspective angle of the centerline and associating this angle with the lateral position error that the vehicle would have at some point ahead of the vehicle if it continued along its current path. Other ways in which motion perspective "streamers" can provide the equivalent of time-advanced lateral deviation are also illustrated by Ringland, et al.,<sup>162</sup> where the ground range to the point of regard is given by  $S$ , which is approximately equal to the relative closing velocity,  $V_G$ , multiplied by the time,  $T_G$ , to travel to that point. The time advance,  $T_G$ , provides a perceptual preview which results in a pure-lead equalization in the effective controlled element dynamics. This, in turn, offsets the undesirable  $K/s^2$  form of the lateral deviation dynamics at low frequency.

<sup>160</sup> Ringland, et al., 1981, op cit.

<sup>161</sup> Weir, David H., and Duane T. McRuer, Conceptualization of Overtaking and Passing on Two-Lane Rural Roads, Franklin Institute Research Laboratory, Technical Report No. 1-193, December 1967.

<sup>162</sup> Ringland, et al., 1981, op cit.

Concluding Remarks. The point of all this is to demonstrate that the pilot's perceptions of changes in altitude,  $h$ , cross range,  $y$ , and ground range,  $S$ , errors are functions of where and how the visual field elements are located in his field of view ( $\beta$ ,  $\gamma$ ,  $\xi$ , and  $\nu$  in Table 8), in this instance, all on the (approximately horizontal) plane representing the earth's surface. Further, these functions can be explicitly quantified. For training objectives in addition to the landing approach, the objective of our research is to develop similar measures of visual element changes with vehicle motions, and various disturbances; and to relate these measures of change to the pilot's ability to perceive or discriminate the change. It will then be possible to assess the fidelity of visual simulation in terms of the distortion, delay, suppression, omission, and/or occlusion of essential cues for a particular training objective.



## ANALYTIC PROCEDURE FOR DETERMINING NECESSARY VISUAL AND MOTION CUE STIMULI

The pilot model concepts outlined in the preceding section form the basis for the fidelity requirements analysis. The methodology uses the analytical techniques of the control engineer to formulate plausible system structures consistent with human pilot characteristics expressed in quantified, mathematical terms. These structures can then be investigated for their sensitivity to distortion or disruption of the visual and motion inputs to the pilot. The results are interpreted in terms of fidelity requirements for pilot training.

The procedure itself does not require inordinate mathematical manipulation and computation. Rather it is the judicious application of modeling techniques discussed previously which requires considerable thought before a plausible and persuasive formulation is achieved. As discussed previously, one of the prime sources of information for this step is the pilot himself. This does not necessarily imply pilot surveys with their tabulations of subjective instrument usage versus task, aircraft type, and training background; although all of these have their place. More important are discussions with pilots on the techniques they use, or think they use, to execute particular flying tasks. Again, as Carter and Semple<sup>163</sup> point out, pilots also should be queried about the possible incorrect performance of a particular maneuver. These verbal descriptions are admittedly fallible, yet can often be translated into the system loop structures discussed previously which can then be examined for consistency with existing pilot model data. The analyst thereby avoids laborious tuning of a performance index or exhaustive consideration of "every possible" structure in favor of the "most likely."

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<sup>163</sup> Carter and Semple, 1976, op cit.

## ANALYTIC PROCEDURE

A concise statement of the analytic procedure is given in Table 11. Let us proceed through this list with a brief discussion of each item and then consider a specific example.

### Compile a Quantitative Description of Components (Step 1)

The first step in the procedure is to gather the material necessary to permit quantitative definition of the key variables for a particular flying task. These include the task itself, the vehicle dynamics, the visual scene kinematics (as appropriate), the display dynamics, the disturbances (and vehicle response properties thereto), and the commands (desired maneuvers, flight paths, etc.). The three longitudinal degrees of freedom<sup>164</sup> (motion in the vertical plane) and the three lateral-directional degrees of freedom<sup>165</sup> (motion in the horizontal plane) are normally uncoupled from one another (neither influences the other) or nearly so, making possible a separation of the system dynamics into two smaller analytical and more manageable pieces. Only very special cases of fixed- or rotary-wing aircraft require coupled longitudinal and lateral-directional dynamics involving six or more<sup>166</sup> degrees of freedom.

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164 Actually there is only one "longitudinal" degree of freedom. This misnomer has come into deliberate and pervasive use for the sake of brevity; because the longitudinal, vertical, and pitching degrees of freedom are always coupled.

165 The third "lateral-directional" degree of freedom is roll and, although not stated, is always coupled with the lateral and directional motions.

166 Additional degrees of freedom can be contributed by structural flexibility in the case of fixed-wing aircraft or by the rotor in the case of rotary-wing aircraft.

TABLE 11

ANALYTIC PROCEDURE FOR DETERMINING MINIMAL LEVEL  
OF VISUAL AND MOTION CUE STIMULI NEEDED TO TRAIN

- (1) Compile a quantitative description of common errors: task, vehicle, piloting technique, and disturbances.
- (2) Identify command (outermost) loops for each task component.
- (3) Determine whether vehicle dynamics permit successful task execution with only the command loops closed.
  - If so only command loops are essential, therefore go to Step 5.
- (4) Determine which additional loops are necessary to permit successful task execution — these additional loops also become essential.
- (5) For each essential loop, look up the catalogued fidelity potential for a specific candidate medium and determine whether this potential permits the required loop closure.
  - If not then simulator training will be compromised for that particular loop.
  - Catalog will include most common or likely student errors

In executing this first step, it is exceedingly helpful to have the benefit of experience in selecting information. Some areas are well defined and documented while others will require extrapolation of data or estimations requiring good engineering judgment. Perhaps the most crucial aspect is strict economy of system parameters without losing the ability to include all critical system effects. Two approaches can be taken:

1. Start with an overdefined system, then weed out unnecessary complication
- or 2. Start with an underdefined system, then add complication as required.

The latter is preferred because it will most quickly provide some degree of "solution" in order to get the analysis process underway. The hazard in this may be the willingness to accept immediately the first solution without qualification.

#### **Identify Command Loops for Each Task Component (Step 2)**

The next step is to establish the likely system loop structure required to regulate against disturbances assuming information for the outermost loops. This is usually visually-derived information only. This may be relatively easy (pilot input strictly governed by explicitly displayed quantities) or more difficult (visual information derived from the pilot's out-of-cockpit view in a multiple loop task). Past experience plays an important role here; but clearly the pilot cannot respond to something if he cannot perceive it; and to control a particular degree of freedom (e.g., pitch attitude, vertical velocity) generally means that perception of it or something closely related to it must be possible.

In most cases the command (outermost) loops will consist of either displacements or velocities. The only acceleration command loop which is obvious is normal acceleration command for fixed-wing air combat maneuvering, and even this may not be appropriate for helicopters.

**Determine Whether Vehicle Dynamics Permit  
Successful Task Execution with Only the  
Command Loops Closed (Step 3)**

The pilot equalization required for the loop structure is established according to the guidance, control, and pilot-centered requirements outlined earlier. System stability is foremost, followed by system performance and workload. Performance is often expressed by loop closure bandwidth or crossover frequency (which can be shown to be near-equivalents) in the absence of specific information on the disturbance being regulated against or the maneuver precision required. At the end of this step, one usually has the basic system model for the no-motion input case where the task is purely one of regulating system error (no command preview, implying  $Y_{p_c} = 0$  in Fig. 27; no motion implying  $Y_{p_m} = 0$  in Fig. 27) using only the visual modality — see Figs. 26 and 29. In rare cases the analysis may show that successful task execution is possible with only the command loops closed, because the equalization requirements do not involve lower frequency anticipation or lead and the performance demands are not great. If this be the case, we can jump to Step 5.

**Determine Which Additional Loops are  
Necessary to Permit Successful Task  
Execution (Step 4)**

If the equalization requirements are extreme (particularly for lower frequency lead) or tightly constrained by performance demands, the vehicle will be troublesome, difficult to fly, and will rate poorly in terms of

pilot opinion or workload for the task under consideration. Even when less extreme, the need for lead equalization signals for potential utility of motion inputs to the pilot. In either case this classification by lead equalization requirements using the compensatory pilot model identifies those flying tasks whenever additional visual information or motion is potentially useful — particularly in the first two phases of the SOP sequence.

Depending upon the task and the skill level of interest, there may be various solutions to this step. For example it may be found that the addition of an intermediate visual velocity feedback loop is all that is necessary to provide adequate pilot-vehicle damping for the execution of a task at the compensatory level. Or it may be necessary to utilize vestibular feedback in order to boost the task execution to a pursuit level. Unfortunately we presently lack adequate quantification of tasks and piloting technique versus skill level to perform this step with confidence, but it is a crucial step to discovery of simulator fidelity needs and therefore will be addressed under research objectives.

The purpose of this step is to elaborate the compensatory loop structures with additional parallel paths responsive to sensed visual rate information or sensed angular and linear accelerations at the pilot location in the aircraft. Current knowledge suggests that equalization possibilities in the vestibular channels are restricted to the known dynamics of these revised pathways coupled with an adjustable gain. The appropriate choice is that gain which allows the lead in the parallel visual channel to be eliminated. The resultant loop structure is known to be capable of somewhat greater crossover frequencies for the system as a whole should the nature of the regulatory task demand it.

The evidence for such structure is most substantial for the angular acceleration motion inputs, somewhat less so for linear accelerations. This is primarily because control of an aircraft's angular motions is fundamental to virtually any flying task and considerable experimental data have been gathered. On the other hand, the pilot's use of proprioceptively perceived linear accelerations appears to be quite task-specific (e.g., flare of the aircraft prior to touchdown). The pilot's awareness

of linear accelerations (and by tentative inference, his use of these sensations) depends in part on his past experience. A background of helicopter flying generally implies a greater awareness of linear accelerations than does the background of the fixed-wing pilot.

**For Each Essential Loop, Look up the Cataloged  
Fidelity Potential for a Specific Candidate  
Medium and Determine Whether This Potential  
Permits the Required Loop Closures (Step 5)**

In this step we compare what we have determined analytically to be necessary with what a given device is capable of. In effect it is the matchup between essential loops required and essential cues available. This presumes the existence of a "cue catalog" for motion and visual devices — a source which does not really exist except in fragmentary form.

Nevertheless if there were a strict accounting of available cue information it would be possible to predict the fidelity potential of a given device in terms of the fidelity parameters listed earlier (threshold, quickness, distortion, and signal-to-noise ratio). Knowledge about the fidelity potential of devices-in-being, in turn, will make it possible to set requirements for future devices.

**OBSERVATIONS ON FIDELITY ANALYSIS**

The experimental work of Ringland, et al.,<sup>167</sup> provides a number of lessons. The experiment consisted of an extremely difficult VTOL hovering task using panel instruments wherein the presence or absence of simulator motion was an experimental variable. That the task was difficult is

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<sup>167</sup> Ringland, Stapleford, and Magdaleno, 1971, op cit.

attested to by the performance variability among the several experimental conditions. Normally system performance remains approximately fixed and pilot opinion (interpreted as subjective workload) changes. One result, surprising at first, was that the elimination of linear motion improved performance relative to the case where both linear and angular motion (presumably most "representative" of flight) were present. The elimination of the linear motion resulted in unrealistic tilting sensations which nevertheless helped the pilot control the simulated vehicle, thus constituting what training psychologists term an "irrelevant cue to correct performance." (Sometimes an irrelevant cue to correct performance is a good thing if it doesn't become a crutch.) Tight attitude control was required by the nature of the task for system stability, and, without these sensations, attitude information was available only visually and more difficult to obtain because of other scanning demands.

The elimination of linear motion in this experiment resulted in a device quite like the World War II vintage Link trainers used for instrument flight training. Pilots trained with this device commented that the real aircraft felt less sensitive or more sluggish relative to the trainer. Pilots back for a "refresher" after extended flight duty typically felt the trainer to be too sensitive. The false, attitude-proportional tilting sensation in the trainer provided additional information not available in the actual aircraft. Subjectively the trainer was more sensitive in its angular motion responses to the controls because an additional source of attitude information was made available to the pilot.

Another major factor in the experimental design<sup>170</sup> was the elimination of motion "washouts," those intentional motion distortions introduced to maintain the simulator's linear travel within the bounds of the simulator. Instead the magnitude of both the linear and angular motions were reduced relative to the real world, to keep linear motions within simulator limits, resulting in accelerations at or below the known thresholds

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170 Ibid.



of the pilot's vestibular senses for much of the time. Thus the performance differences due to motion were considerably attenuated.

These results are quite important for motion simulation. The principal means of reducing the linear travel requirements in motion simulators is the use of one or more variants on the "residual tilt" scheme, a tilting of the simulator cab at sub-vestibular threshold rates to produce linear acceleration sensations while avoiding the linear travel otherwise required. This technique amounts to an intentional distortion of the motion sensations. Whether or not it is acceptable for training in a particular task depends upon the magnitude of the distortion relative to vestibular thresholds. If the distortion is comparable to or higher than the thresholds, analysis following the lines laid down above can determine if the unrealistic cue will influence the pilot equalization adopted. If it does, the training effectiveness is compromised because the pilot equalization differs from that adapted in the real world task.

Motion distortions greater than vestibular thresholds and counter to visual information have the potential of disorienting the trainee to the point where training effectiveness is compromised. This comes about because the pilot has two conflicting sources of information regarding which way is up, or how far he is tilted. His eyes tell him one thing but his vestibular senses tell him another — even to the point where the polarity of the angular rates perceived by the two senses disagrees!

Avoidance of perceptual conflict leads to requirements for large simulator cab linear motion travel. In general there will be amplitudes of motion for a given simulator above which unacceptable perceptual conflict and improper pilot adaptation results. This is particularly true for the pilot who is not simulator-wise and therefore not aware of such conflicts. The research'simulator pilot does not expect realistic motion and is not as deeply affected when he does not get it.

Another perceptual conflict which can be introduced by the simulator is due to time discrepancies between the onset of motion perceived via vestibular senses and that perceived visually. Delays between control inputs and motion responses are a separate problem, even in the actual

aircraft! The pilot will not be able to tolerate time discrepancies much greater than 0.1 sec without complaint. This is particularly true for tasks demanding maximal performance on the part of the pilot, e.g., target tracking, where the crossover frequencies to be attained are relatively high.

At this point it is reasonable to argue that even distorted motion may be of some benefit, provided that the simulator training does not proceed too far. The simulator training will become non-productive when the trainee begins to accept the distorted motion as normal, and to develop precognitive levels of skill on the simulated task. Past this point the trainee will have to unlearn the simulator to learn the airplane.

The problem is to establish when this will occur. Here the methodology outlined above cannot help us because the model does not embody the dynamics of the SOP sequence, i.e., the psychomotor skill acquisition process. This deficiency is a major one, for without being able to predict the speed of learning for a given flying task as represented on a simulator with given motion fidelity limitations, one cannot establish, a priori, its training effectiveness. Considerable analyses of well documented simulator-to-aircraft transfer of training experiments involving flying tasks using moving base simulators are required in this area.

The jet transport flare and landing study cited previously<sup>171</sup> provides us with a relevant case illustrating some aspects of the foregoing procedure as they relate to visual fidelity. The model of the landing task, as determined from flight measurement, indicated a level of closed-loop damping which was more than a simple pure gain feedback of altitude (the command loop) alone could provide. A feedback of vertical velocity or its kinematic equivalent was also required. The large amplitude vertical motion simulator involved in this study did not induce the required level of closed-loop damping. This analysis was a good example of failure to

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<sup>171</sup> Heffley, Schulman, Randle, and Clement, 1981, op cit.

reject the hypothesis that the simulator differs from the aircraft in some property essential to the flare and landing. Hence there was an obvious question of simulator fidelity. What essential cue was either lacking or incorrect?

Analysis along the lines suggested in Table 12 presented some specific possibilities for the apparent simulator deficiencies. Candidate explanations included:

- Excessive threshold for visual vertical velocity information or its kinematic equivalent, vertical flight path angle information<sup>172</sup>
- Lack of pilot lead or anticipation of visual altitude
- Deficient motion (if motion can be used to enhance closed-loop damping)
- Excessive simulator delays or lags (visual update, algorithmic, etc.)
- Incorrect aerodynamic heave damping (slope of lift coefficient versus angle of attack)
- Combinations of the above

This list amounts to fidelity factors which could be checked in order to discover the deficient fidelity characteristics. Or, from another viewpoint, this same list constitutes the features which should be measured and cataloged for the particular simulator components used in order to have predicted their usefulness for the landing task.

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<sup>172</sup> For example, the focus of expansion (of streamers) itself may be diffuse, the reduced field of view may inhibit extrapolation of peripheral streamers to define the focus of expansion, or perspective distortion may contribute to misjudgment of the direction of flight.

TABLE 12

## CONTROL THEORY APPLIED TO THE LANDING MANEUVER

## A LANDING CRITERION:

A "good" landing consists of a significant reduction in sink rate executed sufficiently fast to counter disturbances.

Control implications are therefore

- (1) Adequate "closed loop damping ratio" or "phase margin" or (e.g., damping ratio  $> 0.7$ )
- (2) Highest possible "natural frequency" or "bandwidth" or "crossover frequency" (e.g., natural frequency  $\approx 0.4$  rad/sec)

RAW DATA:



REDUCED DATA:

$h(t)$  matched to second-order differential equation, i.e.,

$$\text{for } \frac{d^2 h}{dt^2} + A \frac{dh}{dt} + B h = 0$$

$A$  and  $B$  solved for best fit to raw data.

## PILOT-VEHICLE INFLUENCES:

There are components of pilot and aircraft in both  $A$  and  $B$ . The aircraft portions are easy to identify:

For  $A$  the aircraft component consists of "heave damping," a predictable quantity which can be estimated or measured directly.

For  $B$  the aircraft component consists of "ground effect," a negligible quantity compared to pilot actions.

After subtracting aircraft effects from  $A$  and  $B$ , the remainder represents the piloting technique component. More specifically,

$$A = A_{a/c} + A_{\text{pilot}}$$

(Negligible)

$$B = B_{a/c} + B_{\text{pilot}}$$

In the case of the landing maneuver

The above criterion forces certain numerical values for  $A$  and  $B$ , and these are confirmed from the flight data.

Also we can characterize fidelity in terms of an equivalence between flight and simulator, i.e.,

$B_{\text{flt}}^{\text{pilot}} = B_{\text{pilot}}^{\text{sim}}$	Good fidelity in terms of height $\rightarrow$ attitude
$A_{\text{flt}}^{\text{pilot}} = A_{\text{pilot}}^{\text{sim}}$	Good fidelity in terms of direction of flight (or sink rate) $\rightarrow$ attitude

- But the actual data show that  $A_{\text{pilot}}^{\text{sim}}$  is nearly zero!

Therefore there is a deficiency in the direction-of-flight loop, an essential loop for this aircraft.

The results of the landing study<sup>173</sup> can be extrapolated to other height control tasks, piloting techniques, and aircraft types if we preserve several constraints. These include basic control theory, the physical laws of vehicle dynamics, and the perceptual pathways implied in the landing situation, i.e., height and direction of flight. Figure 37 shows the results of such an extrapolation for ranges of Army aircraft, both rotary- and fixed-wing, over their respective speed ranges and control techniques. The boundaries shown indicate the amount of height response lag<sup>174</sup> above which direction of flight cues are needed. The conclusions from this plot would be that direction-of-flight cues are required for low-speed helicopter flight (below translational lift) and for low-speed fixed-wing aircraft with relatively high-wing loadings. On the other hand, only altitude cues would be required for fixed-wing aircraft with low-wing loading. Further the boundaries shown could be adapted to any simulator for which direction-of-flight feedbacks were required yet not exhibited by the pilot.

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173 Heffley, Schulman, Randle, and Clement, 1981, op cit.

174 Height response lag is primarily due to "heave damping", a characteristic approximated by the dimensional stability derivative,  $Z_w$ . (See McRuer, et al., 1973, op cit. for a definition of this parameter.) In fact the characteristic time lag due to heave damping equals  $-1/Z_w$ . Additional lag can also be added if there is applicable control lag such as the time required to change attitude.

# TASK: PRECISE CONTROL OF HEIGHT

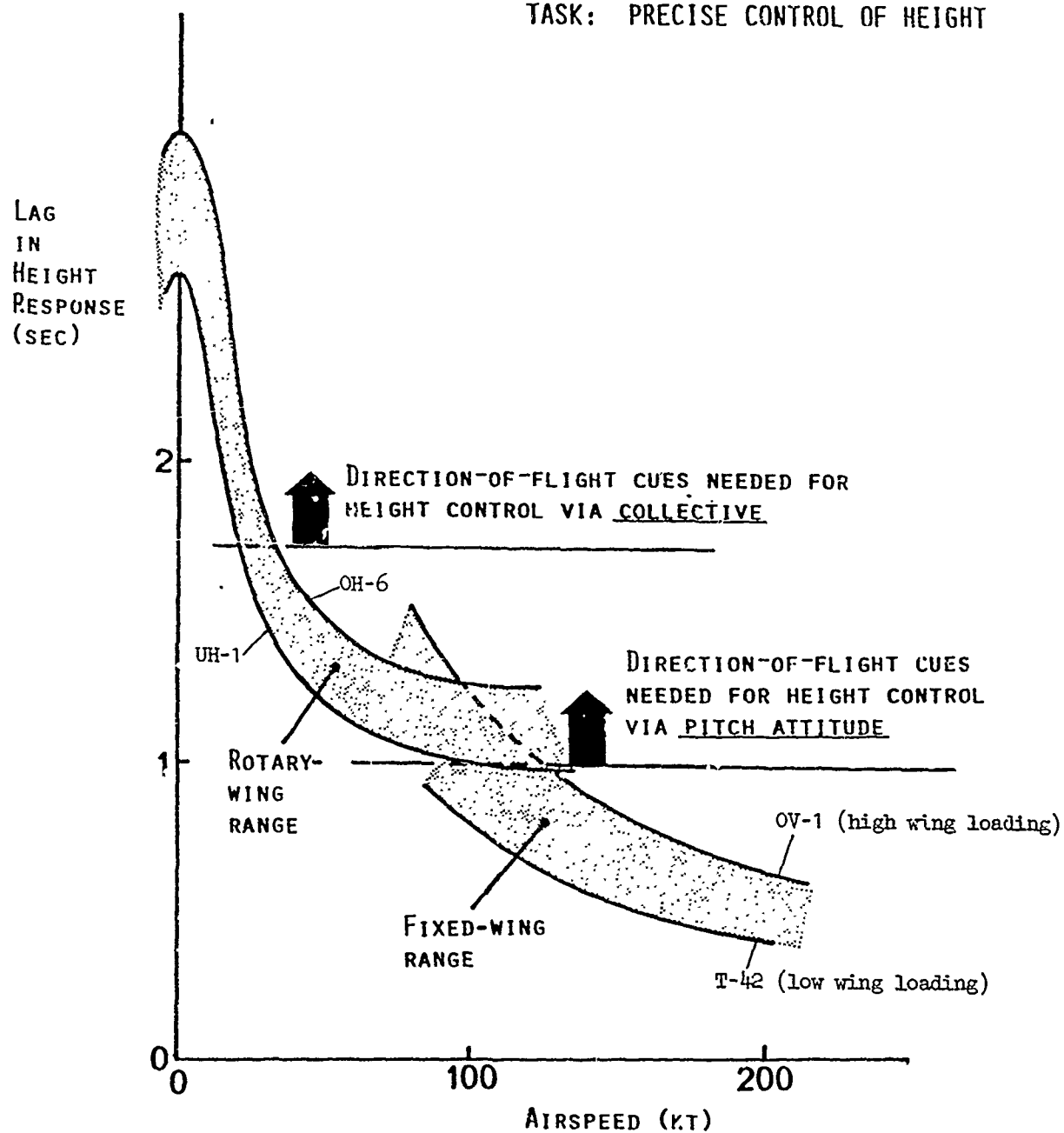


Figure 37. The Need for Altitude Rate Cues Depending Upon Aircraft Type and Piloting Technique

## BOOKKEEPING METHODS FOR SIMULATOR FIDELITY

Our treatment of simulator fidelity thus far has prepared us for the next step — to establish a systematic bookkeeping scheme for simulator fidelity with respect to the array of Army training objectives. This step will take full advantage of our definition of fidelity, our task analysis, the modeling approaches for pilot behavior and perception, and the analytic approach for cue stimulus needed to train.

Simulator fidelity bookkeeping is out of necessity a multidimensional procedure because of the number of factors which must be observed, i.e., task, aircraft type, level of training, and environment. Our ultimate goal is a tradeoff matrix of visual and motion fidelity characteristics needed to train, but this is highly conditional because of the above factors. Therefore it is necessary to introduce intermediate tables and plots as part of our bookkeeping scheme.

One list of useful matrices is suggested in Table 13, and we shall explain each in detail shortly. The value of arranging information in these forms is that it compartmentalizes the data and maximizes its use. Rather than acquiring basic data for each task, level of training, and aircraft type, we have the possibility of finding commonality among both training objectives and training device requirements. Another advantage is that we have, in this kind of list, a ready-made shopping list for the gathering of missing data.

Note that the matrices listed in Table 13 are composed of

- Basic information
- Constructed information

Basic information must be acquired from past research and analysis and from a good deal of future work. Constructed information is based upon analytic procedures such as described in the previous section. Now let us

TABLE 13

A LIST OF BOOKKEEPING FORMS FOR SIMULATOR FIDELITY

- Piloting technique versus task (basic information)
- Cues available versus training device or simulator (basic information)
- Aerodynamic feedbacks versus aircraft type (basic information)
- Essential loops versus piloting task and technique (constructed information)
- Essential loops versus skill level for a given task (constructed information)
- Essential cues available versus essential loops required for a given aircraft, task, and training device (constructed information)
- Training capability by task versus training device (constructed information)
- Macro-detail cues available versus micro-detail features required (Basic and constructed information but not readily obtainable at this time)



consider each of the entries in Table 13 and suggest examples of their form and content.

#### **PILOTING TECHNIQUE VERSUS PILOT TASK**

This is a logical starting point — consideration of how pilots operate an aircraft in order to execute a given task or perform a mission. We have a qualitative description in the training literature, in syllabus material, and from pilot commentary. As stated previously there is little quantification of piloting technique by task in terms which are useful for analysis of fidelity requirements. The form of quantification would most likely consist of a feedback control law formulation in terms of loop gains or, more generally, in terms of loop bandwidths and closed-loop damping (or phase margins). Examples were presented in the cataloged Figures 13 through 22 at the end of the section on Army Missions. It is essential that, for each pilot task to be addressed on a training simulator, there be a well established quantitative description of that task along with the necessary piloting technique required to execute it.

#### **CUES AVAILABLE VERSUS TRAINING DEVICE**

This matrix deals with the perceptual fidelity potential of a specific device. The objective in constructing such a matrix would be to take stock of the special cue availability in existing motion and visual systems. Table 14 illustrates how the matrix might be formulated. Cues would be expressed in terms of convenient state variables (e.g., angular and translational positions and rates for visual; angular and translational rates and specific forces for motion). The quantification of those cues would consist of the fidelity parameters such as threshold, response, distortion, and signal-to-noise ratio.

TABLE 14  
EXAMPLE OF CUES AVAILABLE IN A HYPOTHETICAL SIMULATOR DEVICE

Specific Device	State (Cue)	Threshold	Response	Distortion	Signal to Noise Ratio
Visual Flight Attachment Model No. 101 (Nominal Specifications: 36" x 48" field of view 1000 line raster 30 Hz update Night Runway environment)	Pitch	0.7 deg	30 Hz	A = 150 ft	
	Roll	0.5 deg	30 Hz		
	Heading	2 deg	30 Hz		
	Range	50 ft (perceived)			
	Drift	30 ft (perceived)			
	Altitude	10 ft (perceived)			
	Fwd velocity	4 ft/sec @ 15 ft			
	Side velocity	2 ft/sec @ 15 ft			
	Altitude rate	1 ft/sec @ 15 ft			
	Vertical path	3 deg			
	Lateral path	1 deg			

## AERODYNAMIC FEEDBACKS VERSUS AIRCRAFT TYPE

While most command loops depend almost entirely upon the degree of pilot feedback, a number of supporting loops depend both upon pilot and aerodynamic feedbacks. The nature of those aerodynamic loops, axis by axis, are described in Table 15. Note that the table identifies specific aircraft stability derivatives which can be evaluated for any given aircraft and analyzed to find the net contribution of each derivative to the task in question. To an extent, this kind of analysis has already been performed for some Army helicopters<sup>173</sup>. Similar procedures could be performed for the current inventory of Army fixed-wing aircraft.

## ESSENTIAL LOOPS VERSUS PILOTING TASK AND TECHNIQUE

Refer to Table 6, pp. 55, 56, for examples of pilot control techniques which are more or less independent of the specific Army Flight Training Objectives listed in Table 5, p. 53. Also refer to the block diagrams at the end of the section entitled "Analysis of Army Flight Training Objectives" for examples of more task-specific piloting techniques and corresponding essential control loops. In particular, note the three speed-change maneuvers shown in Figs. 19, 20, and 21. In each case somewhat different essential loops and corresponding cues are involved. It is therefore important to search out these loops within a very specific task and aircraft context.

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173 Heffley, Robert K., Wayne F. Jewell, John M. Lehman, and Richard A. Van Winkle, A Compilation and Analysis of Helicopter Handling Qualities Data. Volume One: Data Compilation, NASA CR 3144, August 1979.

Heffley, Robert K., A Compilation and Analysis of Helicopter Handling Qualities Data. Volume Two: Data Analysis, NASA CR-3145, August 1979.

TABLE 15  
AERODYNAMIC EFFECTS

Control Axis	Stability Primary Derivatives	Stability Derivative Contributors	Remarks
Roll	Bank Angle $\frac{1}{I_x} \frac{\partial L}{\partial \phi}$	Ground effect, $(L_\phi(h))$	Usually stabilizing but negligible
		Wind shear, $L_r \cdot \frac{\partial u}{\partial h}$	Destabilizing
	Roll Rate $\frac{1}{I_x} \frac{\partial L}{\partial \dot{\phi}}$	Roll damping, $L_p$	Stabilizing, a function of wing loading and, for helicopters, rotor type
Pitch	Pitch Rate $\frac{1}{I_y} \frac{\partial M}{\partial \dot{\theta}}$	Pitch damping, $M_q$	Stabilizing, a function of tail geometry for airplane and helicopter at high speed and rotor type for helicopter at low speed
Heading	Yaw Rate $\frac{1}{I_z} \frac{\partial N}{\partial \dot{\psi}}$	Yaw damping, $N_r$	Stabilizing
Surge	Fore/aft Position $\frac{1}{m} \frac{\partial X}{\partial x}$	Wind shear, $X_u \cdot \frac{\partial u}{\partial x}$	Destabilizing
	Surge Velocity $\frac{1}{m} \frac{\partial X}{\partial u}$	Speed damping, $X_u$	Parasite drag, negligible effect for airplane at low speed
Sway	Sway Velocity $\frac{1}{m} \frac{\partial Y}{\partial v}$	Drift damping, $Y_v$	Always negligible, function of vertical fin
Heave	Altitude $\frac{1}{m} \frac{\partial Z}{\partial h}$	Ground effect, $Z_h$	Exponentially increases in vicinity of ground
		Wind shear, $Z_u \cdot \frac{\partial u}{\partial h}$	
	Vertical Velocity $\frac{1}{m} \frac{\partial Z}{\partial \dot{h}}$	Heave damping, $Z_w$	Wing loading and aspect ratio (fixed wing) or disc loading and blade solidity (helicopter)

Table 16 provides another example for landing a fixed-wing light-twin engine aircraft using attitude to control the direction of flight.

#### ESSENTIAL LOOPS VERSUS SKILL LEVEL FOR A GIVEN TASK

One particularly crucial step in the proposed bookkeeping procedure is to document skill level in terms of essential loop structure features. In general we would expect to see a gradual tightening of control loops with increasing pilot proficiency. This would be reflected in any quantification of the overall closed-loop task as well as in piloting technique gains. In addition there may be development of important control cross-feeds from one axis of control to another. (In fact this is typically an indicator of pursuit-level piloting technique.)

Heffley, et al.,<sup>174</sup> and Jewell<sup>175</sup> each describe an example of skill development in the Navy carrier landing task in terms of the development of a pursuit-level technique for controlling flight path and speed. It is pointed out that the use of a control crossfeed (or feedforward) from throttle to pitch attitude can result in a dramatic improvement in flight path bandwidth along with a reduction in pilot workload. Therefore the development of this feature would represent an important objective in skill development.

The reader should refer to Table 6, pp. 55, 56, for examples of compensatory and pursuit skill level techniques which are more or less

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174 Heffley, Robert K., Warren F. Clement, and Samuel J. Craig, "Training Aircraft Design Considerations Based on the Successive Organization of Perception in Manual Control," Sixteenth Annual Conference on Manual Control, MIT, May 5-7, 1980, pp. 119-127.

175 Jewell, Wayne F. Identification of Multiloop Pilot Describing Functions Obtained from Simulated Approaches to an Aircraft Carrier, Systems Technology, Inc., Paper No. 289, presented at the 17th Annual Conference on Manual Control, UCLA, June 16-19, 1981.

TABLE 16

## EXAMPLE OF PILOTING TECHNIQUE VERSUS ESSENTIAL LOOPS

Task	Essential Loops	Indifference Threshold
Landing (fixed-wing, light-twin) using attitude to control flight path	Altitude	2 ft
	Direction of Flight (Vertical)	1 deg @ 0.25 rad/sec
	Drift	4 ft
	Direction of flight (lateral)	?
	Pitch Attitude	0.5 deg

independent of the Specific Army Flight Training Objectives listed in Table 5, p. 53. Also, refer to the block diagrams at the end of the section entitled "Analysis of Army Flight Training Objectives" for more specific examples of essential loops versus skill level for a given task.

#### **ESSENTIAL CUES AVAILABLE VERSUS ESSENTIAL LOOPS REQUIRED**

The next set of features which should be cataloged are the various essential cues which might be candidates for each essential loop in a given task scenario. This information would be valuable in analyzing any deficiencies in essential loop behavior. Table 17 presents some examples for direction-of-flight and attitude.

Evidence for deficiencies in the simulation of essential cues has been found in the following instances:

- Visual height cues from ground texture (or lack thereof)
- Visual direction-of-flight cues (six hypotheses are given on p. 150 and in Fig. 35, p. 135)
- Visual range-to-go to a specific visual element (pp. 187-191)
- Visual image of rotor tip path plane
- Delays in both visual and motion cues (p. 40-41)
- Distortion in motion cues (examples are given on pp. 105-112, 146-149, and 194-206)

TABLE 17

EXAMPLE OF ESSENTIAL CUES AVAILABLE VERSUS ESSENTIAL LOOPS REQUIRED

Essential Loops	Essential Cue Candidates	
	Visual	Motion
Direction of Flight	1) Streamer origin (vertical axis) 2) Derived rate of change of altitude 3) Vertical velocity	1) Quasi-integration of vertical specific force
Attitude	1) Aircraft reference with respect to horizontal (or other earth reference)	1) Quasi-integration of angular rate



## **TRAINING CAPABILITY BY TASK VERSUS TRAINING DEVICE**

An earlier matrix discussed was the cataloging of available cues for extant training devices. It would also be useful similarly to catalog the known training capabilities, by specific task, of existing training simulator systems.

One known example of this kind of data is the airline landing maneuver analysis previous described<sup>177</sup>.

## **MACRO DETAIL CUES AVAILABLE VERSUS MICRO DETAIL FEATURES REQUIRED**

One important kind of bookkeeping information for simulator fidelity is the indexing of "macro detail" cues in terms of "micro detail" features. "Macro detail" refers to certain visual or motion cues in a general sense; for example, the visual presentation of a height cue without regard to which geometric features combine to provide height information. The "micro detail" would be those individual features contributing to the overall height cue — angles, texture, etc.

This is a particularly difficult issue to address because of the redundancy in pattern recognition and the possible variation from one individual to the next in extracting information from a given presentation. The work of researchers such as Wewerinke<sup>178</sup> represents attempts to quantify micro detail information content using optimal estimation methods. Such procedures may provide useful starting points, but the

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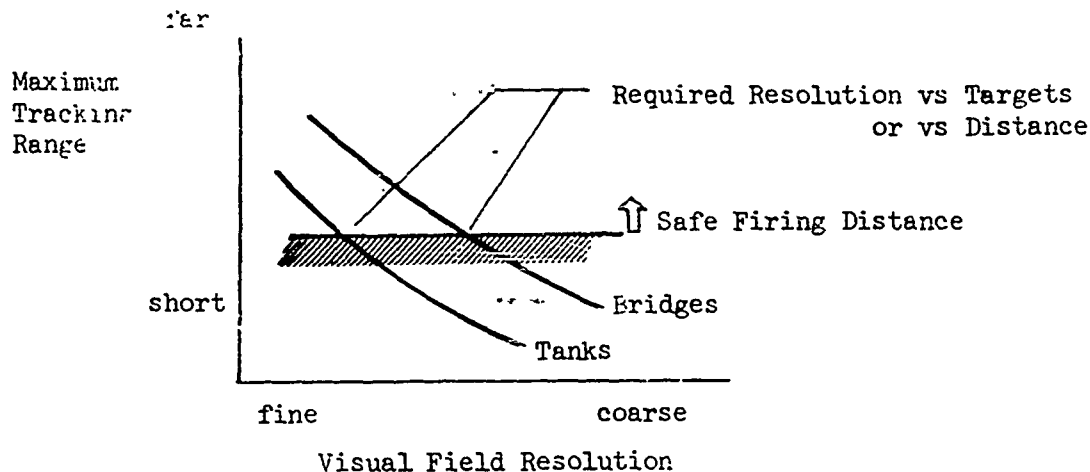
<sup>177</sup> Haffley, Schulman, Randle, and Clement, 1981, op cit.

<sup>178</sup> Wewerinke, 1978, op cit.

results must be validated or refined on the basis of experimental data involving pilot subjects performing realistic flight tasks.

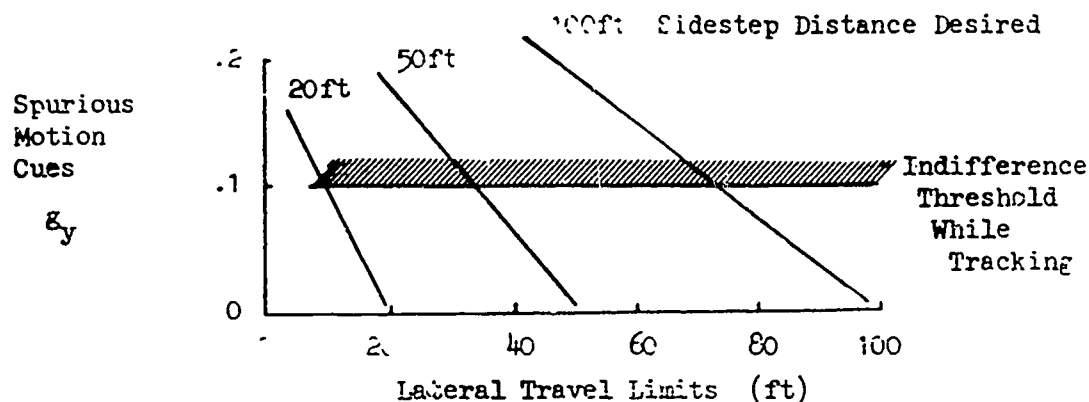
This matter is discussed in several places in this report. For example motion cues in general are discussed on pp. 105-112. Motion cues in support of lateral tracking are discussed on pp. 194-206. Visual range perception is discussed on pp. 187-191. Hypotheses for deficiencies in visual direction-of-flight cues are discussed on p. 150 and in Fig. 37, p. 153. For a given training mission<sup>179</sup> (e.g., helicopter NOE), training objective (e.g., "attack target"), and training medium (e.g., ground-based simulation) — it is possible to determine the tradeoffs among various visual and motion fidelity measures and their training value. Other examples of this form of tradeoff would be as follows:

- Target tracking range versus visual system resolution:

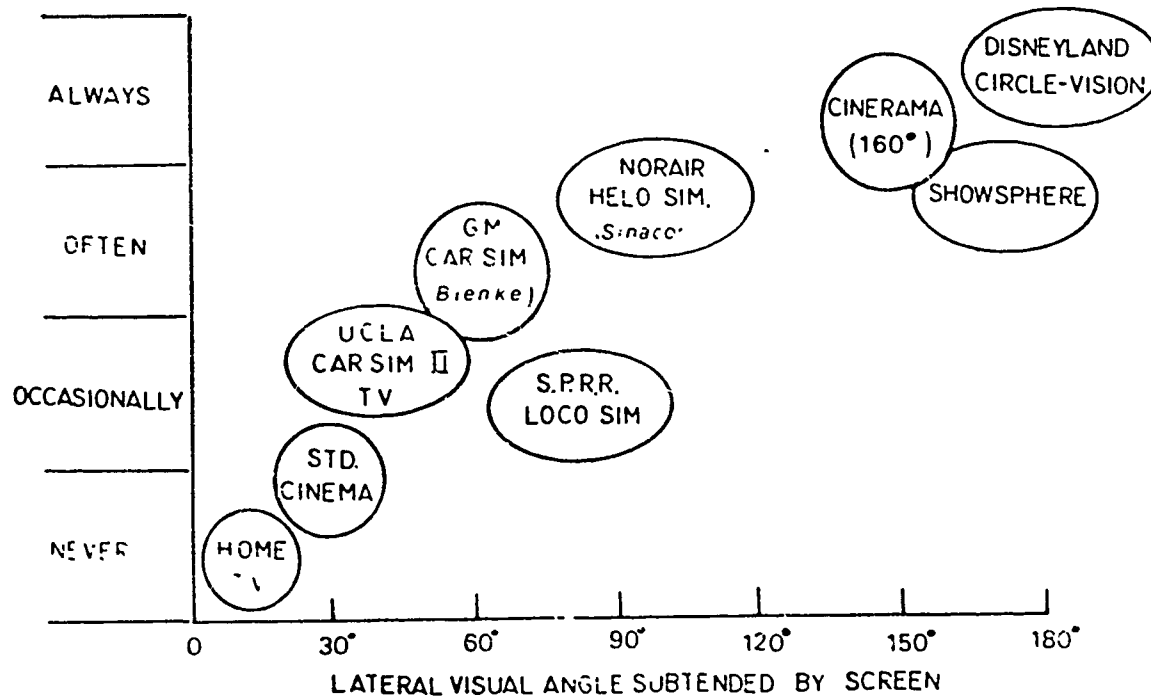


<sup>179</sup> This case corresponds to Aircrew Function D-4.1, "Engagement: Weapon Delivery-Attack Targets," of Table 1 "NOE Operations" in Gainer and Sullivan, 1976, op cit.

- Allowable sideslip alignment maneuvers versus motion system lateral travel:



- Kinetosis versus field-of-view<sup>180</sup>



Anecdotal Experience with Vertigo versus Screen/Size<sup>181</sup>  
When Viewing Driving Scenes From a Fixed-Base Situation

<sup>180</sup> Jex, H. R., D. T. McKuer, R. W. Allen, and J. R. Hogge, Requirements and Program Plan for Simulation Facility and Data Handling for GM Design Staff Safety and Human Performance Group, Systems Technology, Inc., Technical Report 2039-1, March 1974.

<sup>181</sup> Ibid.

Except for the kinetosis tradeoff plot, the above sketches are not based on actual calculations, but have the correct trends and are typical of numerous tradeoffs involving macro detail cues available and micro detail features required.

## RESEARCH NEEDED TO DEFINE SIMULATOR REQUIREMENTS

It has been suggested repeatedly throughout the various sections of this report that additional research must be directed toward the remaining quantification of simulator fidelity components. Major gaps still lie in the pilot perception and piloting technique functions, especially where the use of outside visual information is involved. One of the major objectives of this report has been to describe ways of viewing simulator fidelity which would lead to the identification of missing data and to the ultimate acquisition of those data. The organization of the report, beginning with the definition of fidelity and leading through definition of Army training missions, pilot modeling techniques, analytic procedures, and bookkeeping procedures has, in fact, now led us to the point of outlining topics for additional investigation in Table 18.

The fact that there are presently gaps in the data necessary to define simulator fidelity requirements does not mean that those data cannot be acquired. Various means do exist for obtaining the required information and one of the main goals in this section will be to outline the various methods for collecting empirical data needed to determine simulator fidelity requirements. The examples given are based on some of the Army aviation training missions, although the material presented is nevertheless applicable to many other areas of aircraft operations.

The ideas proposed are aimed at comprehensive quantification of how the pilot operates the aircraft in the execution of a given mission or task. The emphasis is placed on accumulating knowledge of pilot control laws, sensory feedbacks, and decision making rather than on overt task performance (i.e., precision of flight) or pilot opinion. This is in keeping with the notion that training can be equated to correct and appropriate development of feedback loops needed for each stage of flight. We hasten to add, however, that task performance and pilot opinion ratings should also be collected. We believe the more kinds of data obtained, the better the opportunity to gain insight and understanding.

TABLE 18

TOPICS FOR ADDITIONAL RESEARCH:  
TRAINING OBJECTIVES REQUIRING FLIGHT QUANTIFICATION  
OF PILOTING TECHNIQUE<sup>182</sup>

BASIC FLIGHT TASKS

Fixed Wing and Helicopter  
VMC and IMC  
Primary Skill Level Through Continuation Training  
Slow Flight Through Cruise Speeds

HOVERING FLIGHT TASKS

Helicopter  
VMC and IMC  
Primary Through Continuation Training

TAKEOFF/APPROACH/LANDING

Fixed Wing and Helicopters  
VMC  
Primary Through Continuation Training

LOW ALTITUDE OPERATIONS<sup>183</sup>

Helicopter  
VMC Day and Night

WEAPON DELIVERY<sup>184</sup>

Helicopter  
VMC Day and Night

EMERGENCIES

Fixed Wing and Helicopter

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182 See Table 5 for further breakdown into specific piloting tasks.

183 High priority.

184 High priority.

The earlier section which addressed the definition of simulator fidelity described the key background concepts and definitions of terms of which we make use in this report. Perhaps most important is the distinction between implicit fidelity and explicit fidelity, and it is the latter which has been the more elusive to obtain or to quantify. But there are methods — some old, some relatively new — which permit direct and meaningful quantification of explicit fidelity aspects. Simply stated, these are measurement methods which tell us how a pilot flies an airplane or helicopter — the methods address the mechanisms of piloting behavior rather than just the symptoms or results.

Much of the collection of empirical data suggested here is more easily done on simulators, but many of the methods can effectively be made in actual flight — sometimes even using uninstrumented aircraft. We shall indicate where this is feasible.

The organization of this section consists of four main topics:

- Preparatory analysis of piloting tasks
- Measurement tools
- Measurement of piloting technique and pilot perception
- Examples of piloting technique and perceptual measurements and interpretation of experimental results.

The discussion of these topics is followed by a summary.

## PREPARATORY ANALYSIS OF THE PILOTING TASK

Our overall approach to determining simulator fidelity requirements hinges on first, fully understanding the individual task being performed or trained. It is clear that the relative importance and quantitative nature of the various motion and visual stimuli can vary widely. The pilot measurement methods or procedures have to be custom-suited to each individual application.

A formal approach to analyzing piloting tasks has been covered in the section describing the analytic procedure for determining necessary visual and motion cue stimuli; however, we shall summarize that approach for the purpose of discussing methods of collecting data on pilot behavior. The first step in task analysis should be to review written descriptions of the nominal piloting task. For Army training missions, the most systematic description of piloting tasks is given in the aircrew training manuals for various fixed- and rotary-wing aircraft types<sup>185</sup>. These manuals provide the basis for sketching a nominal loop structure which may involve a number of secondary piloting tasks as well as the primary one. An example was shown in Fig. 8 for the helicopter approach to hover piloting task. The primary feature to be noted in this kind of a task description is the approximately parallel structure for the loops involved in each of the three major axes: axial, lateral, and vertical. Within each axis is a nested series loop structure. The outermost loop in each of the series

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<sup>185</sup> Anon., ATM, Utility Helicopter, 1978, op cit.

Anon., ATM, Attack Helicopter, 1978, op cit.

Anon., ATM, Observation Helicopter, 1978, op cit.

Anon., ATM, Cargo Helicopter, 1978, op cit.

Anon., ATM, Surveillance Aircraft, 1978, op cit.

Anon., ATM, Utility Airplane, 1978, op cit.



structures relates to the primary objective in that axis, and the inner series loops act to support that primary objective. For example, in the lateral axis, the primary objective is to maintain a track along the approach centerline; and this is reflected in the outermost loop around lateral position. In direct support of this is regulation of heading and, in direct support of heading, is regulation of bank angle. A similar organization can be observed in other axes and in other piloting tasks. Systematic recognition of such structure is thus the first step in analysis of any given piloting task or mission.

The second step in our task analysis is to estimate the likely ranges of aircraft dynamics or kinematic relationships involved in the task. This is not inordinately difficult, since most fixed-wing or rotary-wing aircraft of a given size and type tend to have very similar dynamic properties, especially if these are aircraft in an operational status and not unusual research or experimental aircraft. For example, in an analysis of the typical properties of single-rotor helicopters by Heffley<sup>186</sup>, it is shown that the major variation in dynamic features among various helicopters is primarily in attitude control characteristics. However, even this aspect is highly predictable with knowledge of the basic rotor type (teetering, articulated, or rigid). The main point to be made is that an estimation of likely ranges of vehicle dynamics is not unduly tied to any particular helicopter model. For the purposes of a preparatory analysis, the differences between, say, an OH-6 and a UH-1 are not great.

The third step in our task analysis is to estimate the likely ranges of bandwidth for each of the loops involved in the task. This can be accomplished on the basis of relatively simple rules of manual, multiloop control theory in combination with available rules of thumb or stated performance objectives. In fact, a dependence on manual control theory ideas is likely to be relatively low. A very good estimation of loop bandwidths is possible by an engineering interpretation of nominal rules

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<sup>186</sup> Heffley, A Compilation of Helicopter Handling Qualities Data.  
Volume Two: Data Analysis, 1979, op cit.

of thumb for each piloting task. Also bandwidths, once established for one loop, are likely to be applicable to the same loop in other tasks. As with the other steps in the preparatory analysis, it is really only necessary to obtain "ballpark" estimates for the various loop bandwidths.

Another dimension of the task loop structure which might be important to measure, and therefore estimate a priori, is the level of successive organization of perception (SOP). Simply stated, this refers to the degree that the pilot is only reacting or whether there is significant anticipation of results and prediction of vehicle response. For example turn coordination can be handled on a "compensatory" level with rudder applied only in response to miscoordination cues — "ball out of center" or pilot perception of lateral g's. On the other hand the pilot can apply rudder knowing "that's about what it takes" to coordinate the turn. This is anticipatory and based on learning how the airplane responds. Such pilot actions might be considered as "pursuit" or even "precognitive" strategy — higher levels of SOP. Some of the features of SOP are summarized in Table 19; and these are perhaps very important targets for measurement.

Let us now consider how we might approach our preparatory planning phase for a particular Army training task, the unmask/remask maneuver. First, we would take an overview in order to see how the task interfaces with other tasks. This may be important in terms of defining fully enough the overall task loop structure. Often any single task is really just constituting an inner loop for a subsequent exterior loop — another more all-encompassing task. As shown in Table 20, the unmask/remask task shows up in various forms of engagement in the attack mission. We would also want to consider other missions (e.g., utility or scout).

Next, focusing on the unmask/remask task itself, we would try to develop the kind of scenario shown in Table 21. Note that this is really just a verbalization of each subtask, things which we could otherwise express in terms of a closed loop block diagram as shown earlier in Fig. 37. The immediate and direct benefit of this kind of exercise is the identification of specific measurements such as how tight is regulation of position (fore/aft, vertical, and lateral), what is the desired pop-up

TABLE 19

SUMMARY CHARACTERISTICS OF PATHWAYS IN PERCEPTUALLY  
CENTERED MODEL OF HUMAN BEHAVIOR

PATHWAYS SELECTED	PERCEPTUAL FIELD CONTENT	ACTION OR OUTPUT	CORRELATES OF TRANSITION AMONG LEVELS OF SOP
Compensatory	Narrow; deviations only	Designed to correct exceedences and reversals; not necessarily rehearsed	Increasing perceptual motor load
Pursuit	Broader; separable inputs, outputs, commands, disturbances in addition to deviations	Designed to correct deviations and to compensate for inter- nal delay; moderately well rehearsed	Increasing rehearsal
Precognitive	Exceedingly broad and ex- tended, even among other individuals and organizations by means of a conference, or recall of past experience, or by recruitment of other resources; separable inputs, outputs, commands, distur- bances only; feedbacks not necessary	Discrete; cued, transient; very well rehearsed	Increasing bandwidth
			Increasing time delay
			Expanding perceptual field content and extension thereof

TABLE 20

TASK BREAKDOWN

(Summarized by Gainer and Sullivan<sup>187</sup>)

Attack Mission Phase:

Enroute — Cruise NOE

- Airspeed
- Altitude
- Heading
- Maintain mask
- Maintain/monitor obstacle clearance
- Determine position/performance intersection

Engagement — Maneuver

- Maneuver into pre-attack position
- Unmask (pop-up)<sup>188</sup>
- Remask
- Perform evade drop-report
- Perform evade dash

Engagement — Pre-Attack

- Hover — instrument check
- Unmask
- Target acquisition
- Remask

Engagement — Weapons Delivery

- Attack
- Hover fire
- Running fire
- Mask

Return to Base — Depart Maneuver Area

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<sup>187</sup> Gainer and Sullivan, 1976, op cit.

<sup>188</sup> Appearance of unmask/remask maneuver indicated by bullets.

TABLE 21

## TASK ANALYSIS OF UNMASK/REMASK MANEUVER

Discussion of Piloting Subtask	Implication on Test Plan, Measurements, and Data Analysis
<p><b>Control of Fore and Aft Position:</b></p> <p>As the pilot ascends toward the top of the mask, whether a stand of trees or steeply sloping terrain, there is a tendency to translate forward. Hence there is an absolute requirement to translate rearward by an appropriate amount during the descent. Also, the pilot is likely to gauge position and vertical path of the helicopter using the tip-path plane to help evaluate tree-top clearance.</p> <p><b>Control of Vertical Position:</b></p> <p>The pilot needs the ability to make a crisp bob-up above the mask, hold altitude precisely for 5 to 10 sec while performing the observation or weapon delivery task, and descend smartly below the mask.</p> <p><b>Control of Lateral Position:</b></p> <p>During the vertical ascent and descent there is likely to be little or no lateral movement. However, following remasking, the pilot will want to translate quickly to a new lateral position below the mask.</p> <p><b>Regulation Against Atmospheric Disturbances:</b></p> <p>Atmospheric disturbances introduce a significant complication in the performance of the maneuver. Turbulence can, of course, affect the attitude and position regulation task through direct action on the vehicle. More insidious is the effect of wind shear at the tree top level or ridgeline. On one hand, a tailwind forces the helicopter toward the vegetation or terrain mask and thus creates a hazard during the descent. Perhaps a more serious condition is a headwind, however. During the unmasking the pilot might trim into the headwind; but during remasking the headwind quickly disappears, forcing the vehicle into the trees or ground. (A Navy counterpart to this hazard has been observed for landing on the stern of a ship.)</p>	<p>The task scenario should involve a terrain or vegetation feature which induces forward translation during vertical ascent and unmasking, e.g., a pyramidal shaped hill, barrier, or tree. In order to gauge position relative to the terrain, a tip-path plane edge should be provided in the outside visual scene. Direct measurements should be applied to control of fore and aft position which reveal the amount of pilot regulation (bandwidth, phase margin) and coordination with height (crossfeed of x-position command with vertical position).</p> <p>Direct measurements should be applied to command and control of vertical position and should indicate bandwidth and level of compensation while unmasked.</p> <p>Measurement of lateral command and control should likewise be applied but will focus on the time interval following remask and descent.</p> <p>A simple random free-air turbulence model would probably suffice in forcing a position dispersion on the airframe/control system combination. The major effect on pilot behavior, however, will be the introduction of a deterministic wind shear at tree-top height. The shear should be applied in both directions, but it can be assumed that the pilot has prior knowledge of which direction. Position bandwidth and compensation should be measured for varying amplitudes and directions of disturbances. Position of the aircraft relative to the obstacle should be plotted for the vertical plane.</p>

trajectory (vertical command), and how much effort is exerted to counter disturbances (gusts, wind shear, terrain.)

At this point we have developed a shopping list of things to measure and, just as importantly, the context in which we want to make those measurements. Now let us consider some measurement methods.

#### THE ARRAY OF MEASUREMENT TOOLS

There is a vast array of measurement tools which are at the disposal of the engineer and psychologist. In selecting these tools, the philosophy should be to use as many methods as is practical in order to gain the broadest perspective and fullest degree of quantification possible. Each flight or simulator situation to be studied should be regarded as a unique target of opportunity which deserves scrutiny from as many points of view or perspectives as is feasible.

In discussing the various kinds of measurement tools, we shall not restrict ourselves to only simulator situations even though that is normally the easiest environment in which to gather data. It is also possible to obtain useful data from actual flight even without using instrumented aircraft, and it is important to note that data taken in flight can carry more credibility than simulator data, even though the flight data acquisition media may be substantially inferior in quality and quantity. It should also be noted that much of the data required to satisfy our needs need not be overly precise. In some cases, we may require only rough verification of our pre-experimental or preparatory task analyses.

Figure 38 shows an array of measurement analysis tools which are appropriate for many simulator facilities. These tools would be most easily implemented on research simulator facilities, but could also be applied to training simulator facilities. Note that the two sources of data are the pilot and the simulator digital computer. Also, the kinds of data are divided into routine versus non-routine (or novel) data.

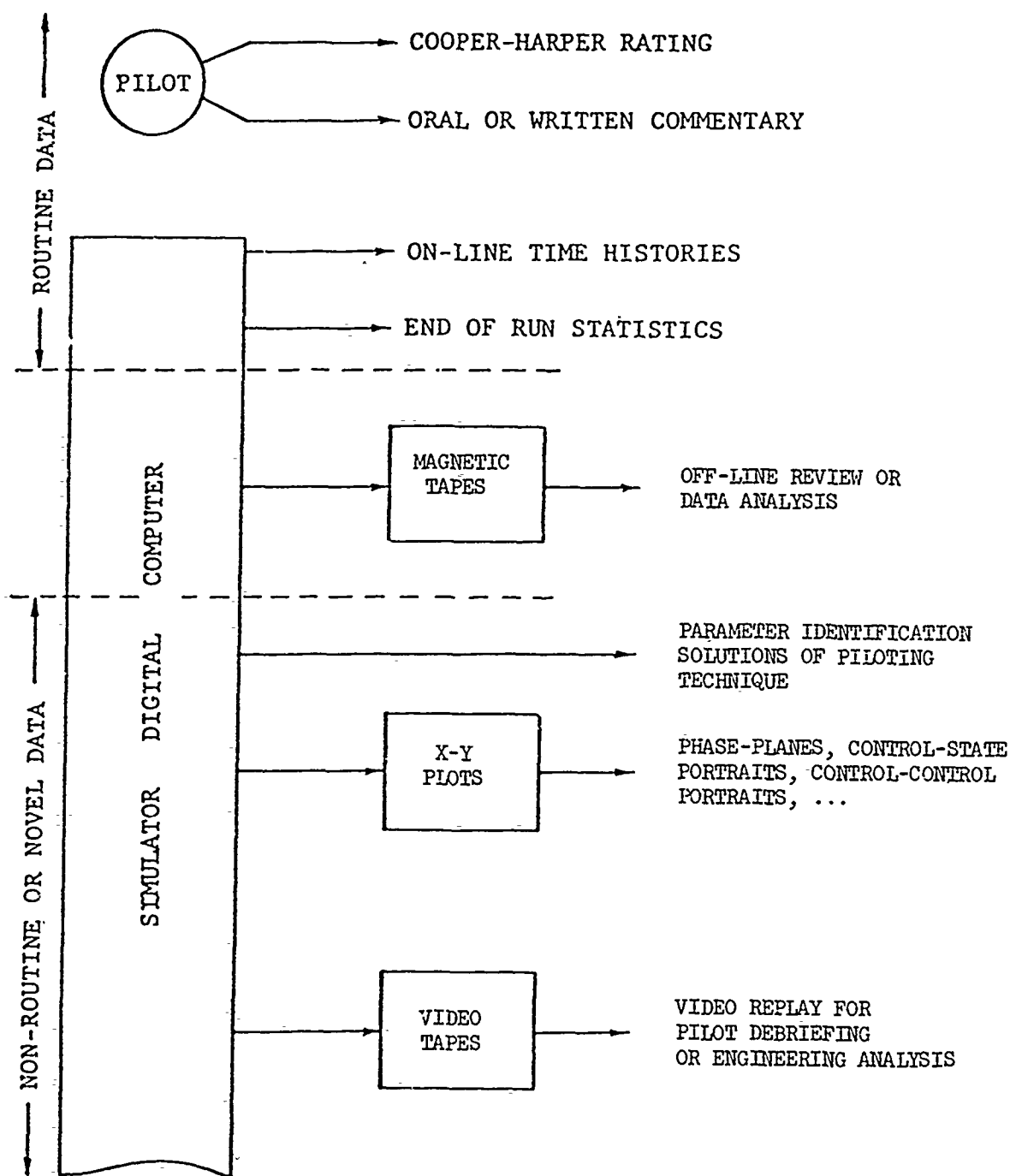


Figure 38. Array of Measurement Analysis Tools

Pilot-centered analysis tools can consist of the standard Cooper-Harper rating<sup>189</sup> and oral or written pilot commentary. Cooper-Harper ratings are really not of any particular value unless a pilot is experienced in giving them, and this usually requires a research or flight test background. On the other hand, oral or written commentary is always possible and is relatively valuable so long as the pilot is sufficiently articulate in describing aspects of the experiment; and even an inarticulate pilot will be able to answer questions posed by the experimenter. One main limitation of pilot commentary, however, is that it is likely to be relatively qualitative. The pilot may be able to make reasonable estimates on overall task performance but will probably not be able to provide details of bandwidth or piloting technique.<sup>190</sup> Naturally the more engrossed the pilot tends to be in a task, the less likely will be the ability for objective self-analysis. Nevertheless, pilot commentary has the potential for providing increased insight when combined with other, more quantitative and direct measurements.

Other routine data sources include gathering of on-line time histories of state variables of interest and the summaries of those time histories in terms of end-of-run statistics. It is the latter of these which is most frequently obtained from simulator experiments. The kinds of statistics normally gathered include means and standard deviations of the various states of interest, such as: control displacement, attitudes, heading, airspeed, altitude, and any special display features which are actively tracked such as glide slope, localizer, or flight director. Unfortunately, these kinds of raw performance statistics tend to be relatively invariant over a wide range of environmental conditions or from one pilot to the next. This is likely due to the fact that most standards of performance do not vary regardless of the situation. For example, even though gusty air may tend to upset or disturb aircraft attitudes, the

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<sup>189</sup> Cooper, George E., and Robert P. Harper, The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities, NASA TN D-5153, 1969.

<sup>190</sup> Carter and Semple, 1976, op cit.



pilot will simply apply more effort to increase attitude bandwidth and thereby retain the same standard of pitch attitude dispersion as was enjoyed in calm air with relatively little effort. Thus the fact that attitude dispersions are about the same in rough air as in calm air implies that the pilot has substantially modified his behavior and is working harder, but these dispersion statistics do not provide a direct measure of that crucial difference. However there are ways to make that important direct measurement using additional statistical measures or raw time history recordings of variables.

A relatively simple way to make bandwidth measurements for a given variable, which is controlled by the pilot, is to divide the standard deviations of the time rate of change of that variable by the standard deviation of the variable itself. In other words, the approximate bandwidth of pitch attitude control is roughly proportional to the standard deviation of pitch rate divided by the standard deviation of pitch attitude. This method would show a significant adjustment in piloting technique between calm air and very rough air even though the standard deviations of attitude itself were nearly the same between the two cases. It should also be noted that this method can always be used as a simple, independent crosscheck of loop bandwidth even though a more sophisticated measurement technique is also being used.

Time history data are frequently believed to be of only limited value. They are sometimes used to determine peak excursions or time between important events, but they are usually not regarded as being particularly indicative of piloting behavior. There are, however, important indicators of piloting technique which are easily derived directly from time history data. The most prominent indicator is usually the dominant oscillatory mode which is readily visible in a variable which is known to be regulated by the pilot. Again, taking pitch attitude as an example, the dominant mode that is normally apparent in a pitch attitude time history, is directly related and, in fact, approximately equal to the pitch attitude bandwidth or crossover frequency. Therefore we need merely to measure the average period over several cycles of the dominant pitch attitude oscillation and divide this average period into  $2\pi$  in order to

obtain a crossover frequency in units of radians per second. This same technique can also be readily applied to bank angle regulation, altitude regulation, and glide slope and localizer regulation. As with the statistical method described previously, the dominant oscillatory mode method can be used as either a primary clue to loop bandwidth or it can be used as an independent check on a more sophisticated measurement approach.

Another important source of simulator data can be magnetic tape recordings of important task variables, which can be stored and reduced at a later point in time. Magnetic tape data is, of course, important where data analysis must be done off-line because of either time or computing limitations.

We show three possibilities of non-routine or novel data gathering methods in Fig. 38. The first of these, parameter identification solutions of piloting technique, is the most sophisticated and can involve a significant amount of off-line data analysis. On the other hand, there are also relatively simple yet effective procedures which can do a good job of quantifying specific features of piloting technique. In general the degree of sophistication required in the identification algorithm will depend upon how specifically the piloting technique loop structure can be characterized. The most notable example of a simple identification scheme is the "NIPIP" algorithm<sup>191</sup>. It has been applied successfully for single and multiloop situations. The NIPIP scheme identifies the piloting technique sufficiently fast to detect significant changes in loop bandwidths or in control strategy itself. Besides the NIPIP algorithm, other available schemes include the describing function analyzer and various maximum-likelihood identification techniques. All are described by Clement, et al.,<sup>192</sup> and a general schematic form for characterizing the identification process is shown in Fig. 39.

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<sup>191</sup> Jewell and Schulman, 1980, op cit.

<sup>192</sup> Clement, Heffléy, Jewell, and McRuer, 1980, op cit.

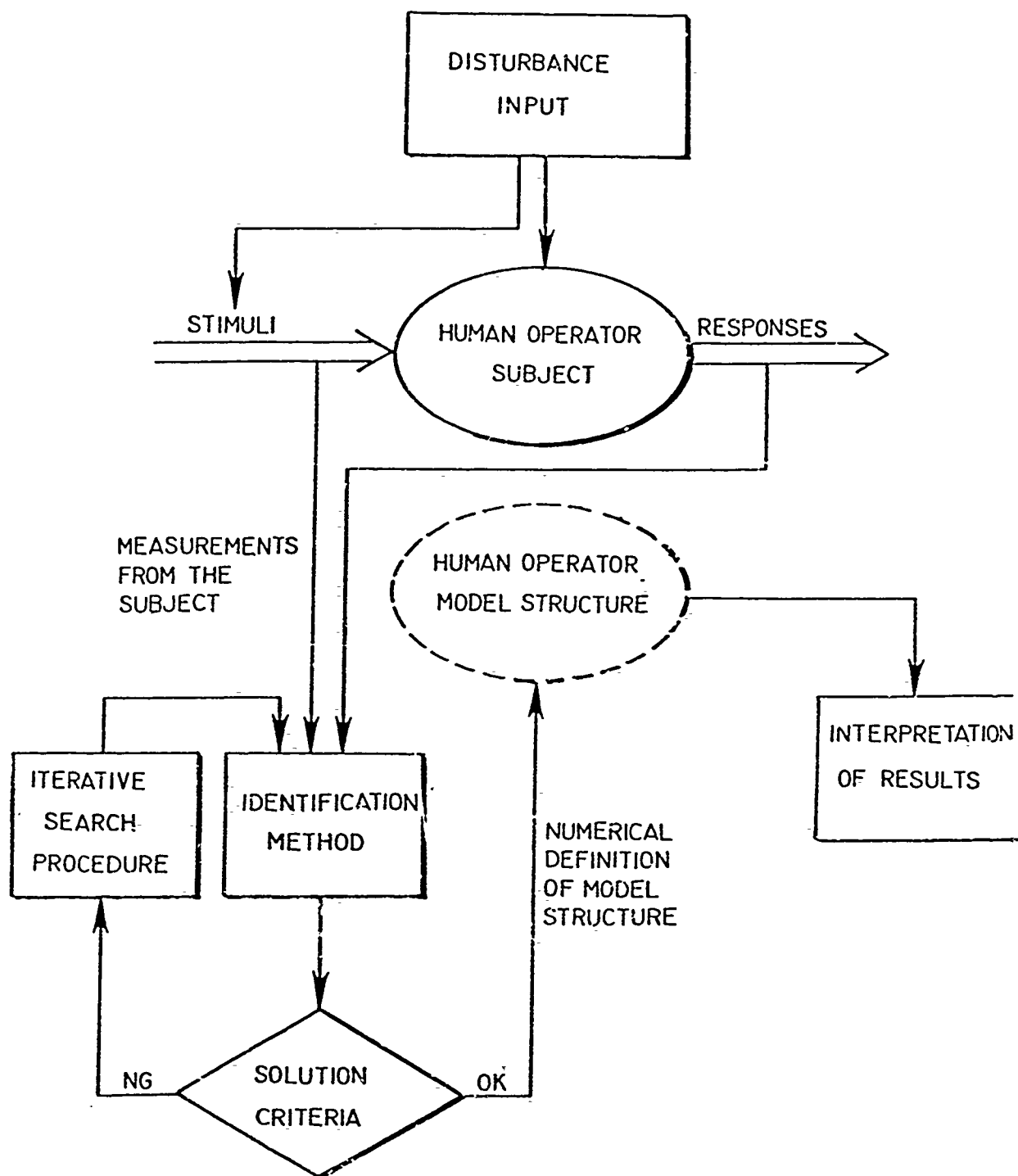


Figure 39. The Identification Process

Another analysis tool not routinely used is direct plotting of phase planes, control-state portraits, and control-control portraits. These are graphic representations of the relationships between selected pairs of state variables in which time is not necessarily represented as a basic independent parameter. For example the closed-loop behavior of the pilot performing a landing flare maneuver has been quantified using a direct plot of sink rate versus altitude and pitch attitude versus altitude<sup>193</sup>. The first of these plots can be interpreted in order to obtain the effective closed-loop frequency and damping of the landing maneuver and the second plot shows the specific control law being used by the pilot to perform this maneuver. This kind of scheme involves minimal instrumentation of either a simulator or aircraft and has, in fact, been used to analyze the differences which result from training for the landing flare maneuver in a simulator as opposed to an actual aircraft<sup>194</sup>.

The final and perhaps simplest of the non-routine analysis tools described here is provision for a video replay of a simulated or actual flight maneuver for the purpose of either debriefing the pilot or for direct engineering analysis. It has been observed that pilots, when reviewing a replay of their own flight, can adopt a more objective point of view for self-analysis and may even substantially change commentary given before that replay. This idea could be extended to include replay of the simulator rather than just video replay.

#### MEASUREMENT OF PILOTING TECHNIQUE AND PILOT PERCEPTION

The direct measurement of piloting behavior, especially psychomotor, has been a popular area of investigation for more than two decades. Much

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<sup>193</sup> Heffley, Schulman, Randle, and Clement, 1981, op cit.

<sup>194</sup> Ibid.

of this activity has been founded upon the pilot-in-the-loop models which have come about through the application of control system theory to the human operator. Unfortunately investigation into the area has been somewhat limited in comparison to what is needed for the relatively expansive full-task context involved in pilot training. Review of available data on piloting technique shows that most investigators have concentrated on inner-loop tasks, such as regulation of pitch and roll attitude. Far less has been done in connection with intermediate- or outer-loop tasks. Some of the reasons for this are that investigation of inner loops reveal considerably more in terms of pilot compensation roles and adoption of higher levels of SOP. Also inner loops tend to involve a correspondingly higher bandwidth and therefore are easier to measure than the lower frequency outer loops whose characteristics can change within a fraction of a cycle of the predominant outer loop frequency. (For example, on a final approach segment the regulation of pitch attitude can involve tens of cycles without significant change in piloting technique while the landing flare is a maneuver executed over only one-quarter cycle of its predominant natural frequency.) Table 22 contains representative examples of available information on piloting technique. While a variety of tasks is listed, one would correctly infer that the data available are sparse in terms of aircraft type, flight phase, and types of cues available. On the plus side, however, the range of tasks shown provides a reasonable point of departure for a large portion of the tasks which are of interest to Army training missions.

Measurement of pilot perception also has received considerable attention but there appears to be fundamental deficiencies in the perceptual data available. As described earlier, motion thresholds appear far larger under realistic task loading than in some laboratory situations<sup>195</sup>. Therefore it is necessary to consider making perceptual measurements while a pilot is performing an actual flight task which involves the modality in question.

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195 Hofmann and Riedel, 1979, op cit.

TABLE 22

## REPRESENTATIVE EXAMPLES OF AVAILABLE DATA

Examples of piloting technique and pilot perception measurements include:

- Attitude and position in hover (simulator — cockpit reference with and without motion references)<sup>196</sup>
- Height, pitch, and roll attitude regulation in cruise (simulator — cockpit reference)<sup>197</sup>
- Glide slope regulation (STOL aircraft simulator — cockpit reference)<sup>198</sup>
- Coordinated turn (simulator — outside visual field and motion reference)<sup>199</sup>
- Landing flare (STOL aircraft simulator — outside visual and motion references)<sup>200</sup>
- Glide slope and airspeed regulation (jet transport simulator cockpit reference)<sup>201</sup>
- Formation-keeping in forward flight under IFR (helicopter — cockpit reference)<sup>202</sup>
- Acceleration/Deceleration (helicopter flight — outside reference)<sup>203</sup>
- Landing flare (in flight and on jet transport training simulator, outside night visual field, cockpit display, motion references)<sup>204</sup>
- Air combat maneuvering, air-to-air gunnery, and air-to-ground stores delivery (simulator — outside visual field, cockpit and motion references)<sup>205</sup>

196 Ringland, Stapleford, and Magdaleno, 1971, op cit.

197 Stapleford, McRuer, and Magdaleno, 1966, op cit.

Stapleford, Craig, and Tennant, 1969, op cit.

198 Hoh, Roger H., Samuel J. Craig, and Irving L. Ashkenas, Identification of Minimum Acceptable Characteristics for Manual STOL Flight Path Control. Volume III: Detailed Analyses and Tested Vehicle Characteristics, FAA-RD-75-123, June 1976.

199 Jex, Jewell, and Magdaleno, 1979, op cit.

200 Heffley, Robert K., Closed Loop Analysis of Manual Flare and Landing, AIAA Paper 74-834, August 1974.

201 Heffley and Jewell, 1979, op cit.

Jewell and Schulman, 1980, op cit.

Weir, D. H., and D. T. McRuer, Pilot Dynamics for Instrument Approach Tasks: Full Panel Multiloop and Flight Director Operations, NASA CR-2019, May 1972.

202 Clement, Allen, and Graham, 1971, op cit.

203 Heffley, A Model for Manual Decelerating Approaches to Hover, 1979, op cit.

204 Heffley, Schulman, Randle, and Clement, 1981, op cit.

205 Hofmann and Riedel, 1979, op cit.

**EXAMPLES OF PILOTING TECHNIQUE AND  
PERCEPTUAL MEASUREMENTS AND INTERPRETATION  
OF EXPERIMENTAL RESULTS**

**Visual Range Perception Throughout  
the Decelerating Approach to Hover  
in a Helicopter**

The manually controlled decelerating approach to a hovering condition in a helicopter has been described as time-varying maneuver for which closed-form solutions of the linear differential equation describing the range-dependent kinematics are not evident<sup>206</sup>. A slightly altered differential equation has been formulated, however, by Heffley<sup>207</sup>, which combines the crossover model of the pilot-vehicle combination (which is described in the section on pilot modeling techniques) with the effects of visual perception<sup>208</sup> and yields a simple manual deceleration guidance law which agrees well with in-flight measurements of the range-dependent kinematics (Fig. 40), which accompany the pilot's control actions. Although the visual manual deceleration guidance law is time-varying, it permits closed-form solutions for speed, acceleration, and time as functions of range to the hovering point. One potential use of the deceleration guidance law, which concerns us here, is as a simulator validation tool by comparing simulator measurements with in-flight

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206 Moen, Gene C., Daniel J. DiCarlo, and Kenneth R. Yenni, A Parametric Analysis of Visual Approaches for Helicopters, NASA TN D-8275, December 1976.

207 Heffley, A Model for Manual Decelerating Approaches to Hover, 1979, op cit.

208 Palmer, Everett, and John Petitt, "A Measure of Psychological Realism on a Visual Simulator," Journal of Aircraft, 14, May 1977, pp. 421-422.

Gilinsky, "Perceived Size and Distance in Visual Space," 1951, op cit.

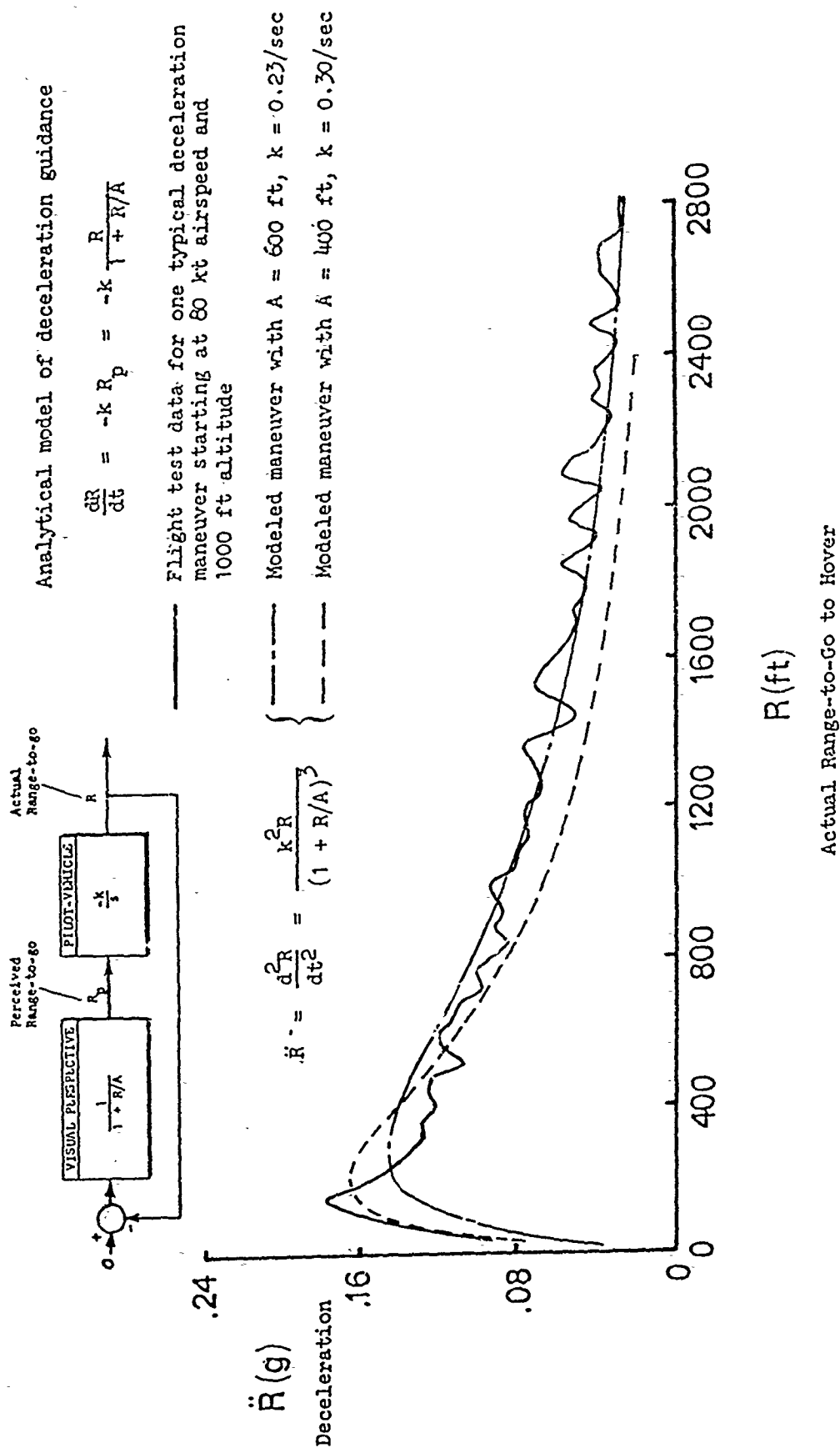


Figure 40. Comparison of Deceleration Profiles Between Analytical Model and Flight Test Data



measurements of the parameters A and k in the deceleration guidance law (Fig. 40) while the helicopter is under visual manual control. In addition the same ideas applied to the deceleration task in Fig. 40 can also be extended to vertical and lateral flight path guidance.

The key to describing (and measuring) the fidelity of the visual perspective (Fig. 40) is provided in Gilinsky<sup>209</sup> where the psychological measurements of apparent range and apparent size of essential cues in the visual field are related to various metrics of visual perspective. There it is shown that perceived range,  $R_p$ , is related to true range, R, by:

$$R_p = \frac{R}{1 + R/A}$$

where the length A is a characteristic measure of perceived range known as the apparent distance of vanishing points from the principles of perspective.

Likewise, perceived size,  $S_p$ , is related to objective true size,  $S_o$ , by:

$$\frac{S_p}{S_o} = \frac{R_p}{R} = \frac{1}{1 + R/A}$$

The value of k in the guidance law can be interpreted as the crossover frequency of the pilot-vehicle system, which represents the psychomotor bandwidth achieved by the pilot in the control task. Values of A and k identified by Heffley<sup>210</sup> from the decelerating helicopter flight tests by

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209 Gilinsky, "Perceived Size and Distance in Visual Space," 1951, op cit.

210 Heffley, A Model for Manual Decelerating Approaches to Hover, 1979, op cit.

Moen<sup>211</sup> are given in Fig. 40 for eventual comparison with corresponding measurements from simulator tests.

Independent out-of-doors field measurements of A were made over twenty years ago by an entirely different technique using comparative apparent size judgments of two plain white isosceles triangles in daylight and reported by Gilinsky<sup>212</sup>. One of the isosceles triangles, called the "standard," was of constant physical size, but was viewed by the subjects at ranges varying from 100 to 4000 ft. The physical size of the other isosceles triangle was adjustable by the subjects, but the triangle remained at a constant range,  $r_o = 100$  ft, and 36 deg to the right of the direct line of sight to the standard triangle in order to prevent simultaneous foveal viewing while the adjustment was being made to match the apparent size of the standard. The experimental site was a fairly level stretch of grassy terrain and the direct line of sight was parallel to an inactive airport runway 5000 ft long.

Since the adjustable triangle is always at range  $r_o$ , its perceived size will be  $s_p = \frac{s}{1 + r_o/A}$ , where  $s$  is the adjusted (objective) true size. The constant size triangle is viewed at varying ranges  $R$ , therefore its perceived size will be  $S_p = \frac{S_o}{1 + R/A}$ , where  $S_o$  is a constant. The subjects were instructed to adjust  $s$  so that  $s_p = S_p$  while using binocular vision. The resulting objective size measurements are then related by

$$\frac{s}{S_o} = \frac{A + r_o}{A + R} = \left(1 + \frac{r_o}{A}\right) \left(1 - \frac{R}{A}\right)$$

<sup>211</sup> Moen, 1976, op cit.

<sup>212</sup> Gilinsky, "The Effect of Attitude Upon the Perception of Size," 1955, op cit.

The length A is thus the subjectively perceived range at which the size ratio  $s/S_0$  tends to vanish. The mean out-of-doors field value of A extrapolated from the measurements<sup>213</sup> was 300 ft.

More recently, similar out-of-doors field measurements in daylight have been repeated and compared with measurements derived from analogous tests while the same subjects viewed collimated and uncollimated closed-circuit TV monitors displaying the same out-of-doors tests. The results for A have been calculated and are listed below based on data from Palmer, et al.,<sup>214</sup>.

Out-of-doors, daylight	530 ft < A < 680 ft
Collimated TV monitor, daylight	216 ft < A < 239 ft
Uncollimated TV monitor, daylight	66 ft < A < 115 ft

These results for A imply that the collimation tended in part to compensate for the distortion of the visual perspective associated with

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<sup>213</sup> Ibid.

<sup>214</sup> Palmer, Everett, Tamara Mitchell, and John Pettit, Angular Size Estimation: A Measure of Simulator Visual Fidelity, (unpublished paper), No date, circa January 1979.

direct viewing of the TV monitor<sup>215</sup>. The range of "out-of-doors" values for A is approximately the same as the range of values for A estimated from the helicopter deceleration flight tests in Fig. 41.

Other analogous measurements have been derived from tests wherein the subjects viewed computer-generated imagery (CGI) consisting of calligraphic night visual scenes of an airport runway beside which the standard and variable triangles were alternately presented for comparative judgment. These results are reported in Palmer and Pettitt<sup>216</sup>, also for collimated and uncollimated viewing. Again the results for A have been calculated and are listed below based on data from Palmer and Pettitt<sup>217</sup>.

Collimated CGI, night scene	$76 \text{ ft} < A < 170 \text{ ft}$
Uncollimated CGI, night scene	$24 \text{ ft} < A < 70 \text{ ft}$

Since the comparable out-of-doors night scene was not tested for comparison, one is left to speculate among hypotheses for the much lower ranges

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215 See Kibort, Bernard R., and Fred J. Drinkwater III, A Flight Study of Manual Blind Landing Performance Using Closed Circuit Television Displays, NASA TN D-2252, May 1964, for results of flight tests of blind landing performance using closed-circuit TV displays with iconoscope lenses having different focal lengths. The average error in touchdown point varied in linear proportion to the focal length of the lens. Thus:

- a) Angular magnification, as with a telescopic lens, caused more undershoots (angular magnification tends to increase A)
- b) Duplication of the perspective caused no mean bias in touchdown error
- c) Angular reduction, as with a wide-angle lens, caused more overshoots (angular reduction tends to decrease A)

216 Palmer and Pettitt, 1977, op cit.

217 Ibid.

for values of A. Again, however, the beneficial contribution of collimation is apparent in increasing the range for A.

To summarize, the apparent distance, A, of vanishing points in the visual perspective can be estimated from a variety of experimental tests in flight and in simulators. The values of A so obtained offer a unique measure of the fidelity of visual perspective for application to the role of simulated visual devices in training. Our recommended technical approach for evaluating the psychomotor fidelity of the simulated visual field also relies on the application of validated mathematical models of human pilot behavior to determine the interactive influence of the following attributes on overall simulator system validity:

1. The displayed variables and control display associations required for the task from the likely loops closed by the pilot to accomplish a given task (i.e., instruments used in IFR, visual cues and field of view requirements in VFR);
2. The dynamic behavior required of the pilot (e.g., describing functions), and hence the piloting techniques exhibited in the given tasks for fixed-base operations;
3. Effects of certain motions on the pilot dynamic behavior including cues likely to be utilized or ignored; permissible dynamic lags and errors in the presentation of simulated visual and motion cues to the pilot;
4. Closed-loop system performance;
5. Pilot commentary and ratings;
6. Excess manual control capacity, i.e., measures of task workload or additional workload that could be accomplished; preferred combinations of displayed variables which are compatible with the physical scanning workload constraint;
7. Scan patterns (for VFR) including proportions of time spent on each fixation within the visual field and link fractions from fixation to fixation; and (for IFR) including proportions of time spent on each instrument and link fractions from instrument to instrument using such tools as the Honeywell oculometer.

## Motion Perception in Target Tracking<sup>218</sup>

In establishing fidelity requirements for the simulation of cockpit motion, consideration must be given to the effects of motion cues on:

- Tracking
- Failure detection

With regard to tracking performance, it is generally more important to have the rotational cues than the translational ones. If tracking performance were the sole criterion, the translational motions might even be eliminated altogether as long as the task did not require a translational acceleration feedback which had no visual equivalent. Nevertheless one must be cautious about providing only angular motion cues in a simulator (which are potentially useful to the pilot), but which are not present in actual flight without providing corresponding specific forces which accompany translation.

On the other hand, the rotary motions should be faithfully reproduced, at least over an appropriate frequency range. A reasonable high frequency limit is 10 rad/sec. This is the approximate bandwidth of the vestibular sensor and is considerably above any manual-control crossover frequencies. For the low frequency limit, it does not appear necessary to go as low as the vestibular sensor washout, roughly 0.1 rad/sec. A conservative

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<sup>218</sup> Stapleford, Peters, and Alex, 1969, op cit.

Ringland, Stapleford, and Magdaleno, 1971, op cit.

Jex, Henry R., Wayne F. Jewell, and Raymond E. Magdaleno, "Effects of Various Lateral-Beam-Motion Washouts on Pilot Tracking and Opinion in the "LAMAR" Simulator," Proceedings of the Fifteenth Annual Conference on Manual Control, AFFDL-TR-79-3134, 1979, pp. 244-266.

lower frequency limit would be 0.5 rad/sec and even 1 rad/sec would be reasonable.

Tracking requirements are also affected by controlled element dynamics. For an easy control task, one requiring little pilot lead equalization, the effects of motion cues are considerably less than for a difficult task, one requiring large pilot lead equalization. Fixed-base results may be completely adequate, although slightly conservative, for a vehicle with good handling qualities. On the other hand, fixed-base results for a vehicle with poor handling qualities or a marginally controllable task will be overly conservative.

The following procedure will be used to estimate motion simulation requirements for a specific tracking situation:

- Define the system — piloting task, vehicle dynamics, displays, inputs, and disturbances
- Determine potential visual and motion feedbacks for the task
- Analyze the flight situation using the Multimodality Pilot Model<sup>219</sup> and, if necessary, the Multiloop Pilot Model<sup>219</sup>
- Reanalyze with a variety of simulator dynamics included (e.g., Jewell, et al.,<sup>220</sup>)
- Determine limits of simulator dynamics for acceptable performance degradation relative to flight.

The second consideration affecting motion simulation fidelity requirements is failure detection. If the piloting task includes recovery from

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<sup>219</sup> McRuer and Krendel, 1974, op cit.

<sup>220</sup> Jewell, Wayne F., Robert L. Stapleford, and Robert K. Heffley, Computed Responses of Several Aircraft to Atmospheric Turbulence and Discrete Wind Shears, NASA CR-152,181, February 1977.

an aircraft, rotorcraft, or system failure, such as an engine or stability augmentation failure, motion cues can play an especially important role.<sup>221</sup> The motions accompanying a failure can help greatly in the pilot's timely detection of the failure. This is especially true if the visual modality is already heavily loaded with a demanding task. For example, a hardover elevator due to a pitch damper failure could be detected by the normal acceleration and pitch rate motion cues before noticeable effects were displayed on the flight instruments (such as the artificial horizon).

At the present no general requirements based on failure detection are available. As a minimum, the motion should be enough to provide an unambiguous clue to the failure. For example, to simulate a hardover yaw damper malfunction, the simulator should have enough lateral travel so that the pilot can clearly separate the lateral acceleration cue accompanying the failure from those due to gusts. In many cases failure detection may put the most stringent requirements on translational motions.

### **Spurious Motion Cues**

Another consideration affecting motion simulation fidelity requirements is realism or false cues. Two specific problems which compromise the pilots' impressions of realism are false translational accelerations and washout effects on open-loop maneuvers. An example of the first would be roll control in a simulator with roll motion but no lateral travel. When the subject rolled the simulator he would sense a proportional lateral acceleration because of gravity, whereas in an airplane the perceived acceleration is generally very small (i.e., the turn is "coordinated"). Not only may the false cue affect the pilot's control

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<sup>221</sup> Caro, 1977, op cit.



behavior, but it will surely influence his subjective opinion of the simulation realism. An example of the washout problem would be a pull-up maneuver in a simulator with limited vertical travel. The initial acceleration would be correct; but, because of the limited travel, it would be necessary to reverse the acceleration quickly. Washout characteristics, which might be completely masked in a tracking task, could become quite obvious in certain open-loop maneuvers.

Several moving-base flight simulator experiments were recently performed using roll and sway motions of the Large Amplitude Multimode Aerospace Research Simulator (LAMARS) of the Flight Dynamics Laboratory at Wright-Patterson Air Force Base, Ohio. The objectives of these experiments were:

- a. To tie in the roll-only results of the four experienced pilots with previous results<sup>222</sup> for four well-trained nonpilot subjects.
- b. To investigate effects of various lateral-beam-motion "washout" filters designed to keep the lateral sway within the  $\pm 10$  ft of LAMARS travel. (Lateral beam sway is used, within limits, to imitate the realistically "coordinated" lateral motions of free-flight roll maneuvers.)

The high-pass washouts on lateral beam travel ( $y_{\text{beam}}$ ) were of the general second-order form:

$$\frac{y_{\text{beam}}}{y_{\text{free flight}}} = \frac{K_y s^2}{s^2 + 2\zeta_y \omega_y s + \omega_y^2}$$

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<sup>222</sup> Jex, H. R., R. E. Magdaleno, and A. M. Junker, "Roll Tracking Effects of G-Vector Tilt and Various Types of Motion Washout," Fourteenth Annual Conference on Manual Control, NASA Conference Publication 2060, November 1978.

where  $K_y$  = attenuation factor,  $\omega_y$  = high-pass break frequency (rad/sec), and closed loop damping ratio,  $\zeta_y = 0.70$  (fixed).

Values of  $K_y$  and  $\omega_y$  were explored, from which example data will be shown subsequently. A nonlinear (time varying) washout was also tested in which  $\omega_y$  was continuously adjusted in accordance with the smoothed magnitude of roll angle so as to permit correct cues for small roll activity, while reducing the lateral beam travel peaks for large roll angles. Reshaping the forcing functions was also investigated and shown to reduce travel requirements.

The pilot's task was to follow an evasive (randomly rolling) target while suppressing gust disturbances<sup>223</sup>. A two-independent-input technique produced behavioral data (describing functions) and performance data (error and control scores), which revealed how pilots used the visual and motion cues. Subjective data were also gathered on the tracking task as well as on limited "sidestep" maneuvers.

The main results<sup>224</sup> show that:

1. The present pilots and previous well-trained non-pilots<sup>225</sup> exhibited nearly identical behavior and performance, implying universality of adaptation and results.
2. The pilots' roll tracking behavior and performance were not significantly affected by a variety of lateral-sway washouts.
3. The nonlinear beam washout filter reduced the peak lateral travels at the expense of occasionally greater lateral-specific-force ( $a_y$ ) peaks, but otherwise did not affect behavior or performance. It promises to provide an adaptive washout which does not need to be

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223 Ibid.

224 Jex, Jewell, and Magdaleno, 1979, op cit.

225 Jex, Magdaleno, and Junker, 1978, op cit.

iteratively fine-tuned to avoid hitting stops while minimizing spurious washout artifacts. Additionally, it should be especially useful during training, where motion cue usage is changing.

4. Both sidestep and random tracking maneuvers gave rise to spurious lateral motion cues (the coordinated free-flight case would have none) which were characterized as "out-of-phase," "like a student on the rudder pedals," etc. Analysis showed these to be roughly correlated by time- and frequency-response parameters related to sway washout gain,  $K_y$ , and frequency,  $\omega_y$ . Combinations of  $K_y$  and  $\omega_y$  were identified which provided the most acceptable impressions of roll and sway motion realism.

We shall now present some of the results which characterize the pilots' judgments of "realism."

Although the pilots were encouraged to use their own words to describe the effects of the motion cues, there was a certain amount of commonality in the terms used by all the pilots. These are summarized below:

1. "Delayed side forces": These were side forces that were seemingly uncorrelated with the roll motion of the aircraft. The specific force,  $a_{y_{cab}}$ , was not completely eliminated by translational acceleration,  $Y_{cab}$ , only attenuated and delayed by the sway axis washout filter. Some pilots said this felt like a student kicking on the rudder pedals.
2. "The leans": These were side forces that were perfectly correlated with the roll motion of the aircraft. The pilots described "the leans" as a pressure either on their knees or shoulders against the bulkhead of the cab when they knew their aircraft was rolled either left or right. Some pilots commented that when they were actively involved in the roll tracking task they did not notice "the leans" but the "delayed side forces" could be

disconcerting. (Note here the conditional dependence of the utricular threshold on task workload.)

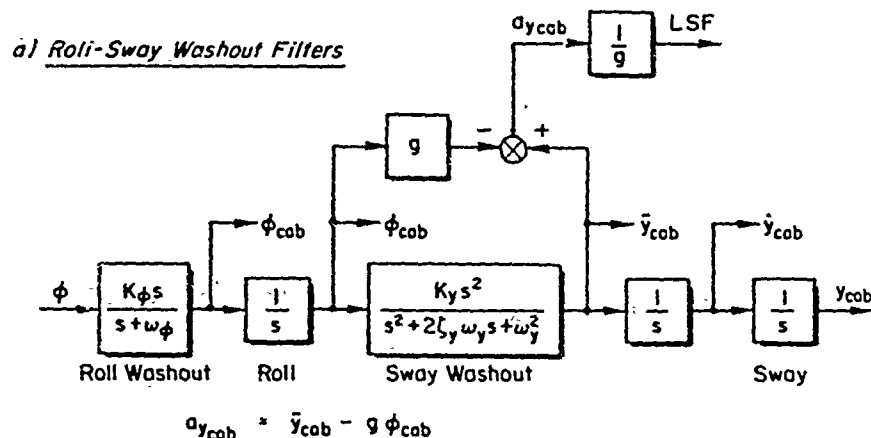
3. "Change in the effective roll axis": The pilots felt that the effective roll axis was above them for roll-only motion. However for combined roll and sway motion the pilots could discern changes in the effective roll axis for various types of sway axis drive logic (i.e., various combinations of  $K_y$  and  $\omega_y$ ). This made the pilots feel as if they were on the end of a variable-length pendulum as  $K_y$  and  $\omega_y$  were changed.
4. "Change in stick sensitivity": Although not a consistent comment, some pilots could discern changes in the effective stick gain for various types of sway-axis drive logic. This affected their impression of the task difficulty (e.g., "easier to fly now," or "more difficult to track now").

The pilots' subjective impressions of the motion cues, as described above, were used to define boundaries of acceptable combinations of the parameters of the sway-axis washout filter. The resulting "boundaries" are summarized in the plot of  $K_y$  versus  $\omega_y$  shown in Fig. 41 (from Jex, Jewell, and Magdaleno<sup>226</sup>). The boundaries shown in Fig. 41 intentionally appear nebulous for three reasons:

1. Pilot comments were not always repeatable, and many times the pilots admitted that the changes in the motion cues due to changing  $K_y$  and  $\omega_y$  were very

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<sup>226</sup> Jex, Jewell, and Magdaleno, 1979, op cit.



b) Comments

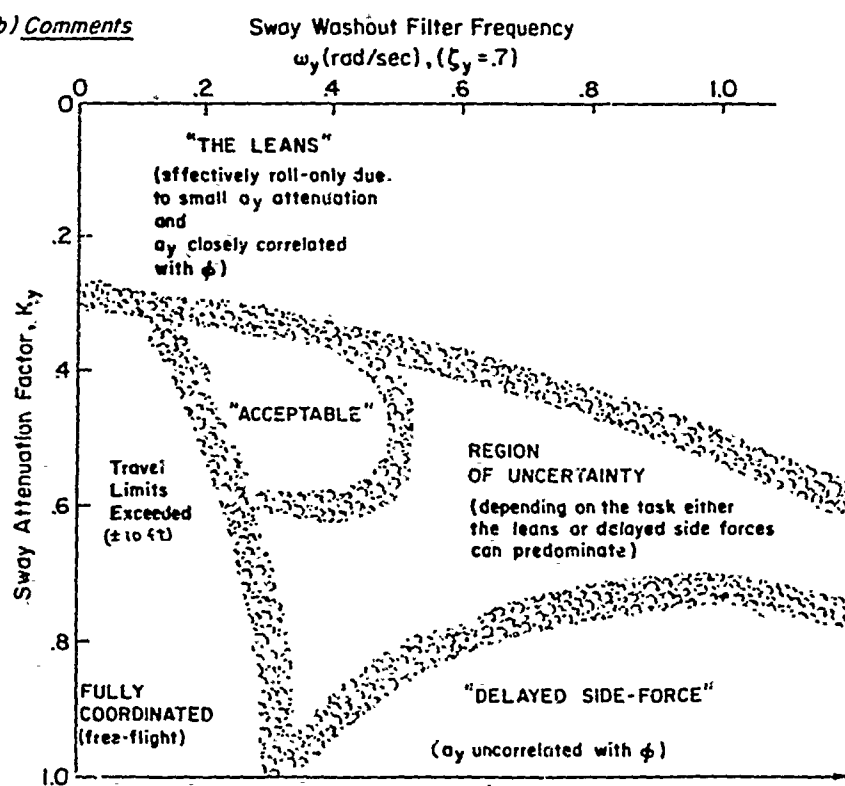


Figure 41. Boundaries of Sway-Axis Washout Filter Parameters (From Jex, Jewell, and Magdaleno<sup>227</sup>) Which Delineate the Pilots' Impressions of Realism From Combined Roll and Sway Motion Cues

227 Ibid.

subtle. Therefore only relative judgments could be rendered, and the pilots' subjective impressions of the motion cues were a function of the starting points of the  $K_y$ ,  $\omega_y$  combination. The pilots were not told which combination of  $K_y$  and  $\omega_y$  was being used, but they were told when a change in the value of either  $K_y$  or  $\omega_y$  was made. This experimental technique was adopted because it was very difficult for the pilots to rate the motion cues on an absolute scale.

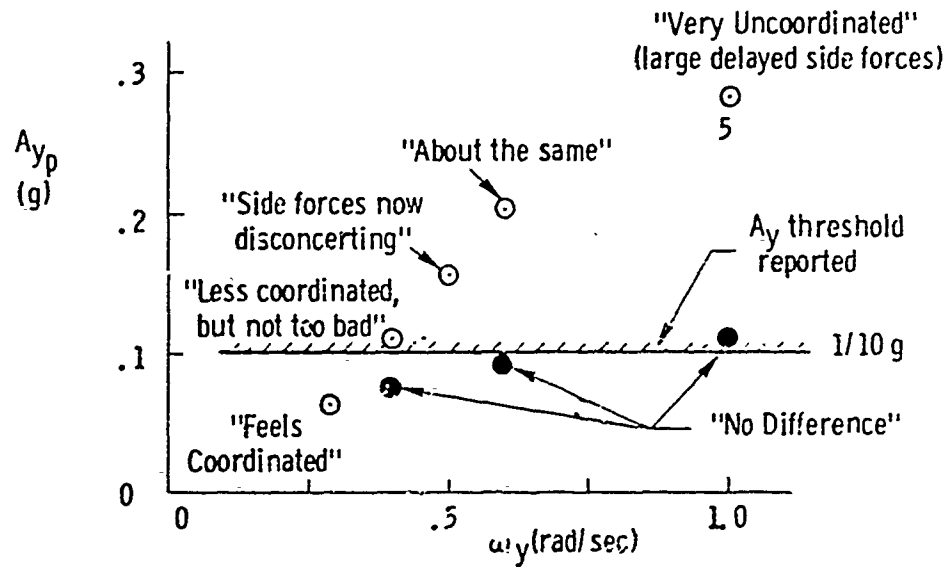
2. Pilot comments changed with the magnitude of the target's randomly rolling motion. The pilots were much more sensitive to changes in  $K_y$  and/or  $\omega_y$  for the larger rolling amplitude than for the reduced amplitude. The difference in the pilot commentary is probably due to an indifference threshold on specific force (Roark and Junker<sup>228</sup> report the  $a_y$  indifference threshold to be approximately 0.1 g).
3. Pilot comments changed with the task. This too was probably related to the pilots' indifference thresholds to specific force. For example, Fig. 42a summarizes some pilot comments on a plot of peak  $a_y$  versus  $\omega_y$  for  $K_y = 0.9$ . For bank and stop (sidestep) maneuvers the side forces become "disconcerting" when  $\omega_y$  is greater than 0.4 rad/sec (note that this is where the  $a_y$  peaks become greater than 0.1 g), but for the tracking task with the reduced input the pilot said "no difference" between  $\omega_y = 0.3$  and 1.0 rad/sec (note that the  $a_y$  peaks just reach 0.1 g for  $\omega_y = 1.0$  rad/sec). A similar phenomenon occurred when  $\omega_y$  was

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228 Roark and Junker, 1978, op cit.

- Bank and stop maneuvers.
- Roll tracking with "reduced" input.

a) PEAK SPECIFIC FORCE VS.  $\omega_y$  AT  $K_y = .9$



b) PEAK SPECIFIC FORCE VS.  $K_y$  FOR  $\omega_y = .3$

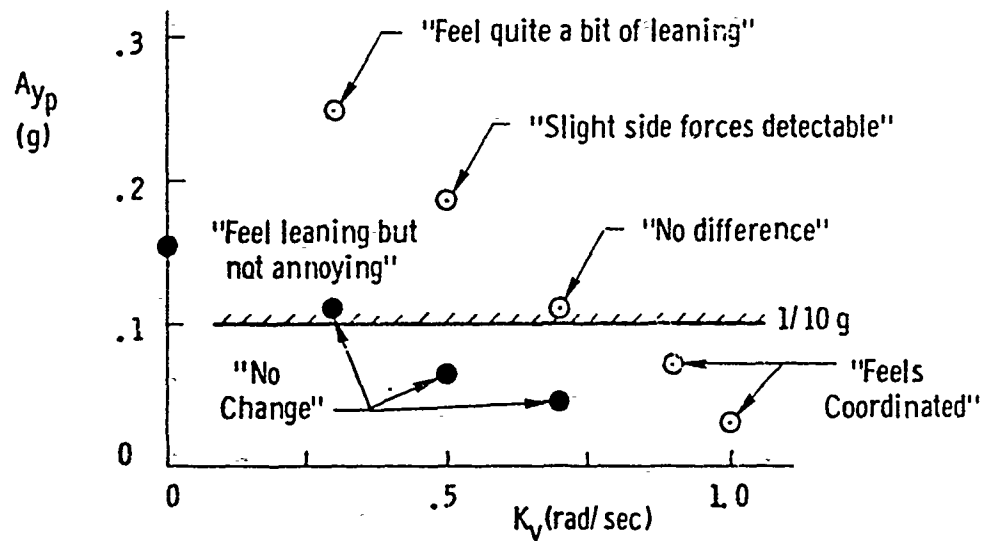


Figure 42. Summary of Pilot Commentary for Bank and Stop Maneuvers and Roll Tracking

fixed and  $K_y$  varied, as shown in Fig. 42b. Also note from Figs. 42a and 42b that for small values of  $K_y$  with  $\omega_y = 0.3$  rad/sec the pilot complained about the "leans," whereas for large values of  $\omega_y$  with  $K_y = 0.9$  the pilot complained about "lagged side forces."

Finally one other important comment was the pilots' universal displeasure with hitting the sway displacement limits. The adverse effects of hitting displacement limits have been observed in other simulators (e.g., Jewell, et al.,<sup>229</sup>) and should be prevented by adopting nonlinear motion drive logic.

The nonlinear washout filter had the predicted attribute of preventing the sway displacement from hitting the LAMARS limits, because the amount of lateral travel used is extremely sensitive to  $\omega_y$  (recall that  $\omega_y$  is self-adaptive for the nonlinear filter). Otherwise back-to-back comparisons of the linear and nonlinear washout filters with the same value of  $K_y$  revealed no consistent differences in the pilots' subjective impression of the motion cues. The tracking scores obtained with the linear and nonlinear filters were virtually identical, and the pilot describing functions were also the same. However the amount of lateral travel used by the nonlinear filter was usually 30 percent less than that used by the linear filter during roll tracking. Except for occasionally greater peaks, this reduction in lateral travel was not otherwise accompanied by an increase in specific side force,  $a_y$ .

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229 Jewell, Wayne F., Warren F. Clement, Lt. Col. Thomas C. West, USA (Ret.), and Dr. S. R. M. Sinclair, Powered-Lift Aircraft Handling Qualities in the Presence of Naturally-Occurring and Computer-Generated Atmospheric Disturbances, FAA-RD-79-59, May 1979.



## MOTION PERCEPTION SUMMARY

In summary, fidelity requirements for the simulation of cockpit motion depend on the psychomotor role of motion cues in tracking and failure detection tasks as well as on the pilots' impressions of realism.

With regard to the pilot's tracking performance and behavior, it is generally more important to reproduce correct rotational motion cues over an appropriate frequency range which will be predicted from validated analysis of the specific tracking situation using the Multimodality Pilot Model and, if necessary, the Multiloop Pilot Model. Nevertheless one must be cautious about providing only rotational motion cues in a simulator (which are potentially useful to the pilot) but which are not present in actual flight without providing corresponding specific forces which accompany translation.

The simulation of motions accompanying a failure will help greatly in the pilot's timely detection of the failure. This is especially true if the visual modality is already heavily loaded with a demanding task. At the very least the motion should be sufficient to provide an unambiguous clue to the failure. In many cases failure detection may put the most demanding requirement on translational motions.

Two specific problems which compromise the pilot's impressions of realism are false translational accelerations and washout effects on open-loop maneuvers. Roll motion without sway motion provides an exaggerated proportional gravitational component of lateral acceleration which is unrealistic. An example of the washout problem is provided by a pull-up maneuver in a simulator with limited vertical displacement. Although the initial acceleration would be correct, it would be necessary to reverse the acceleration unrealistically because of the limited travel.

Roll and sway motion cues have recently been investigated with the aid of the Air Force Flight Dynamics Laboratory's Large Amplitude Multimode Aerospace Research Simulator (LAMARS). Various linear and nonlinear sway motion washout filters were designed and tested to keep the sway

displacement within the  $\pm 10$  ft of LAMARS travel. The main results from this investigation show that:

- The pilots' roll tracking behavior and performance were not significantly affected by a variety of lateral-sway washouts.
- The nonlinear beam washout filter reduced the peak travels at the expense of occasionally greater lateral-specific-force ( $a_y$ ) peaks, but otherwise did not affect behavior or performance. It promises to provide an adaptive washout which does not need to be iteratively fine-tuned to avoid hitting stops while minimizing spurious washout artifacts. Additionally it should be especially useful during training where motion cue usage is changing.
- Both sidestep and random tracking maneuvers gave rise to spurious lateral motion cues (the coordinated free-flight case would have none) which were characterized as "out-of-phase," "like a student on the rudder pedals," etc. Analysis showed these to be roughly correlated by time- and frequency-response parameters related to sway washout gain,  $K_y$ , and frequency,  $\omega_y$ . Combinations of  $K_y$  and  $\omega_y$  were identified which provided the most acceptable impressions of roll and sway motion realism.

## SUMMARY FOR PLANNING AND COLLECTING MEASUREMENTS

The purpose of this section is to outline various methods for collecting empirical data needed to determine simulator fidelity requirements. As shown, this involves not only the measurement tools themselves but also the preparation for their use and the judicious interpretation of their results.

Some of the principles considered important to the data collection process include:

- Being sensitive to the task being examined, its context, and its components.
- Being eclectic in applying measurement techniques — several approaches may produce insight and are not necessarily much more expensive than just one.

Table 23 is offered as a checklist for setting out to obtain empirical data whether from simulator or flight.

TABLE 23

A CHECKLIST FOR PLANNING AND COLLECTING MEASUREMENTS  
OF PILOT BEHAVIOR

- Establish purpose, scope, and scenario

- Elect part- or full-mission simulation

- Specify mission phases, events, environment

- Organize responsibilities, procedures, tasks for each crew member within each mission phase delineated by events

- Specify inputs, types of activity (e.g., cognitive or psychomotor), outcomes, and outputs associated with each task

- Perform essential pre-experimental analysis

- Prepare activity time line analyses for normal and emergency operations together with likely alternatives for procedural errors which are foreseen

- Classify non-intrusive measurements for the purpose of identifying errors, piloting techniques, unusual pilot actions, and degraded pilot rating

- Procedure-centered evaluation based on time-sequences of all variables and events

- System performance-centered evaluation

- ✓ Command-following bandwidth or latency and critical exceedences

- ✓ Disturbance regulation bandwidth or latency and critical exceedences

- ✓ Safety; operational capability (distributions of state variables)

- Human operator-centered evaluation

- ✓ Pilot acceptance (distributions of state and control variables)

- ✓ Temporal averages of task-specific dynamic behavior among crew members

TABLE 23 (Continued)

- ✓ Subjective ratings - appropriate workload indices for full-mission simulation

- Objective workload correlates
  - Psychophysiological correlates
- } Useful for part-task simulation.

(Note that objective workload correlates are useful for "calibrating" subjective ratings and psychophysiological correlates are useful event markers)

- ✓ Eye Point of regard: useful for event markers, temporal and ensemble distributions of attention

Define measurement support and structure organization, and specify formats and media for output variables to be measured and recorded

- Discrete outputs, events
- Continuous signals to be sampled
- Continuous signals without sampling
- Closed-circuit video
- Audio communications
- Hard copy (e.g., subjective ratings and observers' notes)

Estimate likely parameter values for proper and improper execution of activities within normal and emergency procedures

Dry run portions of experiment and refine measurement techniques

Specify output variables to be fitted by distributions from which probabilities can be estimated for the purpose of safety analysis verification and for interpretation in terms of decision analysis and workload analysis

- Manage and monitor data acquisition during experiment

Check against pre-experimental analysis

Look for measurement deficiencies

Keep up to date with as many on-line measurements as possible

Relate measurements to commentary and observations

TABLE 23 (Concluded)

- Post experimental analysis

Analyze interrelationships among

- Procedure-centered measurements
- System performance-centered measurements
- Operator-centered measurements

Identify or postulate sources of human error and workload

Perform planned statistical analyses (if any) and update hypotheses

Refine behavioral models

Recommend improvements to measurement procedures

Organize and present results

- General recommendations

Treat data as archival

Acquire as much numerical definition as is practical (may be limited by storage and non-interference requirements)

Do not restrict data acquisition to the narrow objectives of the experiment; it may serve someone else 10 years hence!

## CONCLUSIONS AND RECOMMENDATIONS

Human operator control theory, combined with adequate quantitative description of Army training objectives, offers a powerful potential for determining simulator fidelity requirements. The full exploitation of this potential, however, must await the gathering of crucial data which describe piloting technique and pilot perception during specific flight tasks and operating environments.

A few significant examples have been identified which indicate how to analyze and interpret simulator fidelity questions and obtain quantitative results and answers. These examples tend to be associated with outer-loop piloting tasks in critical flight phases, such as nap-of-the-earth maneuvering and fixed-wing landing flare.

An operational definition of simulator fidelity has been proposed in a manner which unifies control theory and pilot training notions. Simulator fidelity is considered to be the degree to which perceivable states are present which are essential to inducing correct psychomotor and cognitive behavior for a given task and environment. If training is the development of essential feedback loop structure for a given task or training objective, then we may consider fidelity as being reflected by the essential cues which are available to the pilot to close the essential loops.

The term "explicit fidelity" has been tied to the combination of pilot perception and piloting technique exhibited in the simulator as compared to that exhibited in an actual flight situation. Thus explicit fidelity carries with it the ideas of perceptual fidelity. A more incidental kind of fidelity can be associated with the actual simulator software and hardware characteristics, those features which are normally considered to come under the heading of objective or engineering fidelity. One important result of this report has been to show how the explicit simulator characteristics of piloting technique and pilot perception can be quantified.

The first step in establishing simulator fidelity requirements is the quantitative description of the piloting task or training objective. This constrains the pilot-aircraft scenario so that control theory analysis tools can be systematically applied. Much of this quantitative description can be obtained from existing training documents such as the ATMs.

The major missing elements which preclude an immediate, across-the-board analysis of fidelity needs are:

1. The systematic measurement of piloting technique in a real-world environment.
2. Measurement of perceptual transfer functions under appropriate task loadings.
3. Determination of how the micro-details of a modality medium (especially visual) convey composite state information.

The first two elements above would permit a systematic accounting of the fidelity potential which is available in existing simulator or training device motion and visual systems. With the addition of the third item from the above list, it would be theoretically possible to predict requirements for given training objectives.

Essential cues, the root of simulator fidelity requirements, issue from essential loops; and, in many cases, these loops are easy to identify from task descriptions. For such cases, where only the command loops are essential, fidelity requirements tend to be relatively clear; but the requirements may not be as clear for critical fidelity conditions where loops intermediate between the command and innermost loops are also essential.

Essential loop structure can be inferred from relatively simple measurements made of actual flight maneuvers. In one example, dealing with the landing maneuver for large jet transport aircraft, strong evidence was found for an essential direction-of-flight loop in addition



to the more obvious and essential altitude loop. When viewing this same maneuver on a particular training simulator there was little or no evidence of this important direction-of-flight loop in most cases, and it was presumed that there was a deficiency in the direction-of-flight cue available to the pilot. While it has not yet been possible to discover the exact source of the cue deficiency in this case (either motion or visual) it has been possible to tabulate a bounded list of candidates for the fidelity problem. The most plausible of the various alternatives in this case was a deficiency in visual direction-of-flight information due to the restricted field of view. For the fidelity potential exhibited in this particular simulator, a sample extrapolation was made from the airline jet transport to various Army fixed- and rotary-wing aircraft and their respective piloting techniques.

A procedure was devised which would provide an analytic determination of essential cue information required to accomplish a given training objective, but systematic execution of this procedure would be seriously hampered by lack of basic data describing piloting technique and pilot perception in flight. The procedure itself involves reasonably simple and common feedback system analysis tools.

A bookkeeping scheme has been suggested which would aid in gathering basic data for use in simulator fidelity determination. This bookkeeping scheme consists of a number of matrices which can be used to describe the various components of simulator fidelity. This bookkeeping scheme has the additional benefit of pointing out where there is commonality of training objectives with regard to simulator fidelity. Furthermore it would permit extrapolation to training objectives not yet defined or to aircraft types not yet designed and built.

Additional research is required to define the missing elements which were previously listed. This research centers around quantifying piloting technique and pilot perception under appropriate task loading in flight and in corresponding training simulators. These kinds of measurements should constitute the next major steps in simulator fidelity research. It should be recognized that this research can be accomplished with various levels of effort ranging from occasional targets of opportunity to a full-

blown, intensive research program intended to fill out large portions of the missing data. Clearly the time required to obtain meaningful simulator fidelity definition depends upon the intensity of the research effort.

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## GLOSSARY

The following definitions of terms are useful for understanding the methodology for approaching simulator fidelity presented in this report.

<b>Bandwidth</b>	An indication of how quickly a system responds to a command or disturbance. Bandwidth is usually expressed in terms of frequency, i.e., the inverse of time, thus an alternative to expressing system response in terms of bandwidth is to use an effective response time or rise time.
<b>Command Loop</b>	The outermost control loop necessary for the execution of a given task or subtask. For example, for a guidance task, the lateral command loop would be heading; for a navigation task, the lateral command loop would be track or course deviation error.
<b>Control (variable)</b>	Any of the variables which the pilot must manipulate in order to fly the aircraft (or simulator).
<b>Crossover Frequency</b>	Numerically similar to bandwidth but, strictly speaking, it is the frequency at which the open-loop pilot-vehicle transfer function is equal to unity. Crossover frequency can also be likened to an effective loop gain.
<b>Describing Function</b>	A counterpart of the transfer function which is restricted to the frequency domain and which may be valid for only a limited range of amplitudes. A describing function can be used to portray any of the components of the pilot-simulator or pilot-vehicle system.
<b>Direction of Flight</b>	The directional aspect of a velocity vector can include flight path angle, vertical velocity, or any state variable combination equivalent to them.
<b>Disturbance</b>	Any unwanted variable which affects the aircraft (or simulator) response.

<b>Essential Cue</b>	A cue which is required to close an essential loop.
<b>Essential Loop</b>	One of possibly several loops which are necessary to perform a given task. A command loop is an essential loop as are the various inner supporting loops or control crossfeeds.
<b>Equations of Motion</b>	The set of mathematical relationships which describe the behavior of a given system component or the combination of several components. A number of factors may be included in a set of equations of motion such as Newton's second law of motion, aerodynamic effects, and pilot psychomotor and cognitive behavior.
<b>Explicit or Intrinsic Fidelity</b>	The specific and appropriate behavior of a pilot which, if exhibited in a simulator situation for a given task, would lead to successful execution of the same task in an actual flight situation. Specifically, this involves both the piloting technique and pilot perceptual transfer functions essential for the task and is therefore intrinsic to the task.
<b>Extrinsic or Implicit Fidelity</b>	See incidental fidelity.
<b>Feedback</b>	The use of a portion of a system state variable to influence a system control. The purpose of feedback is usually to provide stability and to minimize errors.
<b>Feedforward</b>	The direct application of a portion of a system command to a control. The purpose of a feedforward is usually to quicken response or offset lags imposed by feedbacks. Another form of feedforward is a crossfeed from one control to another in order to reduce crosscoupling effects.
<b>Frequency Domain</b>	The expression of system dynamic properties with frequency appearing as an independent variable. For example, the quickness of a response could be expressed in terms of "bandwidth," "natural frequency," etc.
<b>Heave Damping</b>	An important aerodynamic characteristic which is most commonly addressed in terms of the partial derivative of specific z-force due to a unit change in the component of aerodynamic velocity along the z-axis, i.e., $Z_w$ . Heave damping

represents the basic flight path response of an aircraft due to a rotation in attitude, activation of a direct z-force control, or the action of a vertical gust component. Heave damping can be estimated for any airplane or helicopter, based only on gross weight and geometry of the wing or rotor blades.

**Incidental (or  
Extrinsic or Implicit)  
Fidelity**

The counterpart of explicit fidelity involves the specific description of the simulator response and aircraft model which may contribute to providing fidelity but which do not expressly describe the piloting technique and pilot perception which have to be learned to perform the task. Incidental fidelity can be roughly equated to objective or engineering fidelity.

**Inner Loop**

Usually a supporting loop for some task or flight objective. The most common and the most important inner loops are usually pitch attitude and bank angle.

**Intermediate Loop**

A supporting loop which is sometimes necessary to bridge the gap between a piloting task and the basic vehicle dynamics. For example, in a navigation task, it is frequently necessary to provide an intermediate guidance loop between the outer navigation loop and the inner control loop.

**Kalman Filter**

A form of optimal estimation based on a quadratic weighting of the uncertainty in measurements relative to the variance of states.

**Laplace Operator**

A way of representing time derivatives or integrations with respect to time. The Laplace operator,  $s$ , is substantially equivalent to the derivative operator,  $d/dt$ . Similarly, the inverse,  $1/s$ , is equivalent to  $\int dt$ . Using Laplace operators, linear differential equations can be restated as transfer functions between controls and state variables.

**Objective Fidelity**

Those characteristics of a training simulator which can be quantified by direct measurement of physical characteristics of hardware and software.

**Outer Loop**

A general term including command and intermediate loops. In general an outer loop is more influenced by the task description than by the vehicle dynamics.

<b>Perceptual Fidelity</b>	Characteristics of those aspects of a simulator which the pilot uses to obtain essential cues or characteristics of those behavioral aspects of the pilots themselves.
<b>Pilot Gain</b>	A numerical quantity which describes any of several relationships between a given pilot cue and the command or control actions resulting from that cue.
<b>Pilot Perception</b>	The transfer function which relates an actual motion or visual quantity and the information derived by the pilot about that quantity. Pilot perception can involve threshold, response time, distortion, or signal-to-noise aspects.
<b>Piloting Technique</b>	The specific control laws exhibited by a pilot which produce commands or control movements based on the pilot's perception of stimuli.
<b>State (Variable)</b>	Any of the dependent or independent variables which describe the aircraft (or simulator) response to controls and disturbances.
<b>Time Domain</b>	The expression of system dynamic properties with time appearing as an independent variable. For example, the quickness of a response could be expressed as a "rise time to 50 percent," a "lag time constant," etc.
<b>Training Objective</b>	Usually a specific piloting task or subtask which is related to a specific aircraft or aircraft type, operating environment, and involves a particular skill level.
<b>Transfer Function</b>	An operational mathematical expression of the functional dependence of one state variable upon another or upon a control variable or a disturbance.